```
      IF(NCALC.EQ.2)GO TO 38
C
C  PRESSURE CALCULATIONS
C
      WRITE(6,50)
      WRITE(6,51)
      WRITE(6,52) (YR(J),J=1,NYRP)
       DO 35 I=1,N
       WRITE(6,60)I,X(I),Y(I)
       DO 30 II=1,NYRP
       TSEC=TCONV*YRINC(II)
       SUM=0.
       DO 25 J=1,M
       IF (TSEC-T(J).LE.0.) GO TO 25
       STEI=(PHI*VISC*C*CF1)/(4.0*(TSEC-T(J)))
       FINEI=(((X(I)-XW(J))**2)/XK)+(((Y(I)-YW(J))**2)/YK)
       IF(FINEI.LT.EPS) GO TO 30
       X1=STEI*FINEI
       CALL EIX(X1,FUNC)
       SUM=(FUNC*Q(J))+ SUM
 25    CONTINUE
       AP=(VISC*CF2)/(4.0*PI*((XK*YK)**.5)*H)
       HALF=AP*SUM
       PRES1(II) = PINIT+HALF
 30    CONTINUE
       WRITE(6,61) (PRES1(II),II=1,NYRP)
 35    CONTINUE
      IF(NCALC.EQ.1)GO TO 555
C
C  PRESSURE CALCULATIONS FOR ISOBAR PLOT
C
 38   CONTINUE
      RW=(RW/12.)*4.5
      NTOTW=NWP+NI
      CALL PLOTS(0,0,5LPLOTR)
      CALL DRWPAD(FXMIN,FXMAX,FYMIN,FYMAX)
      CALL SKETCH(XW,YW,M,14,0)
      CALL SKETCH(X,Y,N,1,0)
      CALL SYMBOL(3.0,10,1.0.3,14HAREA OF REVIEW,0.,14)
      CALL SYMBOL(7.0,10,05.,10,14,0.,-1)
      CALL SYMBOL(7.2,10.0,.10,24HINJECTION WELL LOCATIONS,0.,24)
      CALL SYMBOL(7.0,9,9..10,1,0.,-1)
      CALL SYMBOL(7.2,9,85,.10,24HABANDONED WELL LOCATIONS,0.,24)
      CALL SYMBOL(7.0,9.75,.10,4,0.,-1)
      CALL SYMBOL(7.2,9,7..10,30HSTATIC MUD COLUMN+GEL STRENGTH,0.,30)
      CALL SYMBOL(7.2,9.55,.10,23HPRESSURE(PSI) ISOBAR = ,0.,23)
      CALL NUMBER(999.,999...10,PRBAR,0.,2)
      DO 301 J=1,NTOTW
      XTEST=ABS(FXMIN-XW(J))
      YTEST=ABS(FYMIN-YW(J))
      IF(((XTEST**2)+(YTEST**2)).LE.(RW**2)) FXMIN=FXMIN+RW
 301  CONTINUE
       DO 300 K=1,NIBAR
       XP=FXMIN
       YP=FYMIN
       TSEC=TCONV*YRPLOT
 323   CONTINUE
       SUM=0.0
       DO 302 J=1,M
       IF(TSEC-T(J).LE.0.) GO TO 302
       STEI=(PHI*VISC*C*CF1)/(4.0*(TSEC-T(J)))
       FINEI=(((XP-XW(J))**2)/XK)+(((YP-YW(J))**2)/YK)
```

```
      IF(FINEI.LT.EPS) GO TO 303
      X1=STEI*FINEI
      CALL EIX(X1,FUNC)
      SUM=(FUNC*Q(J))+ SUM
302   CONTINUE
      AP=(VISC*CF2)/(4.0*PI*((XK*YK)**.5)*H)
      HALF=AP*SUM
      PRESP=PINIT+HALF
303   CONTINUE
      XPOLD=XP
      XP= XP+XINC
      IF((XP.GT.FXMAX).AND.(YP.GT.FYMAX))GO TO 400
      IF(XP.GT.FXMAX)GO TO 304
      DO 305 J=1,M
     IF((((XP-XW(J))**2)+((YP-YW(J))**2)).LE.(RW**2)) GO TO 303
305   CONTINUE
      SUM=0.0
      DO 306 J=1,M
      IF(TSEC-T(J).LE.0.)GO TO 306
      STEI=(PHI*VISC*C*CF1)/(4.0*(TSEC-T(J)))
      FINEI=(((XP-XW(J))**2)/XK)+(((YP-YW(J))**2)/YK)
      IF(FINEI.LT.EPS) GO TO 312
      X1=STEI*FINEI
      CALL EIX(X1,FUNC)
      SUM=(FUNC*Q(J))+SUM
306   CONTINUE
      AP=(VISC*CF2)/(4.0*PI*((XK*YK)**.5)*H)
      HALF=AP*SUM
      PROLD=PRESP
      PRESP=PINIT+HALF
312   CONTINUE
      IF((PROLD.LT.PRBAR(K)).AND.(PRESP.GT.PRBAR(K))) GO TO 307
      IF((PROLD.GT.PRBAR(K)).AND.(PRESP.LT.PRBAR(K))) GO TO 307
      GO TO 303
307   CONTINUE
      PDIF1=ABS(PRBAR(K)-PROLD)
      PDIF2=ABS(PRESP-PROLD)
      XP=(((XP-XPOLD)*PDIF1)/(PDIF2)) + XPOLD
      CALL SYMBOL(XP,YP,.1,ISYM(K),1)
      GO TO 303
304   CONTINUE
      YP= YP+YINC
      XP=FXMIN
      GO TO 323
400   CONTINUE
300   CONTINUE
     CALL PLOT(0.0,0.0,999)
555  CONTINUE
5     FORMAT(8F10.0)
9     FORMAT(8I10)
11    FORMAT(10A6)
47    FORMAT(59H1 WELL      WELL COORDINATES          FLOW RATES     INIT
     1IAL)
48    FORMAT(60H   ID          X(FT)      Y(FT)           (GAL/MIN)      TIME(
     1YRS))
49    FORMAT(/,1X,I3,6X,F9.2,3X,F9.2,7X,F6.2,5X,F9.2)
50    FORMAT(73H1 OBSERVATION   PT. COORDINATES          BOTTOM HOLE PRESS
     1URE(PSI) BY YEARS)
51    FORMAT(29H     POINT        X(FT)     Y(FT))
52    FORMAT(1H+,33X,1A6,4X,1A6,4X,1A6,4X,1A6,4X,1A6)
60    FORMAT(/,3X,I3,6X,F8.1,1X,F9.1)
61    FORMAT(1H+,33X,F6.1,4X,F6.1,4X,F6.1,4X,F6.1,4X,F6.1)
```

```
 70  FORMAT(67H1 FIELD DATA:                    RESERVOIR                    FORM
    1ATION FLUID)
 71   FORMAT(74H                              POROSITY     THICKNESS     VISCOSITY
     1   COMPRESSIBILITY)
 72   FORMAT(70H                              (FRAC.)       (FEET)          (CP)
     1       1/(PSIA))
 73   FORMAT(/,10X,F5.3,9X,F5.1,8X,F6.3,10X,F10.9)
 74   FORMAT(//,65H0                         INITIAL        FORMATION PERMEABILI
     1TY      WELL)
 76   FORMAT(66H                              RESERVOIR         (MILLIDARCIES)
     1     RADIUS)
 77   FORMAT(66H                              PRES.(PSIA)       X-DIRECT      Y-DIRECT
     1       (IN.))
 78   FORMAT(/,10X,F8.2,7X,F7.1,6X,F7.1,7X,F5.2)
      STOP
      END

      SUBROUTINE EIX(X,XEI)
C
C  SUBROUTINE TO CALCULATE THE EXPONENTIAL INTEGRAL USING THE
C  INFINITE SERIES METHOD
C
      DATA EPMS,GAMMA/1.E-10,0.5772156649/
      XEI=-GAMMA-ALOG(X)
      I=0
 8    I=I+1
      FACT=1.
       DO 6 J=1,I
       XJ=J
 6     FACT= FACT*XJ
      XI=I
      FNEG=-1.0
      TERM=((FNEG)**(I+1))*((X**I)/(XI*FACT))
      XEI=XEI+TERM
      IF (TERM.LT.0.0) TERM=-TERM
      IF (TERM.LT.EPMS) GO TO 7
      GO TO 8
 7    CONTINUE
      RETURN
      END
```

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VITA

Stephen Eugene Barker was born in Norwich, New York, on November 8, 1950, the son of Jacke Marie Barker and Stuart Harold Barker. After completing his work at New Berlin Central High School, New Berlin, New York, in 1968, he entered the United States Army. Upon discharge from the Army in 1973, he entered the State University of New York College at Oneonta, New York. He received the degree of Bachelor of Science from State University College at Onenota in December, 1976. In September, 1976 he entered the State University of New York at Buffalo, New York. He received the Bachelor of Science in Engineering from the University of Buffalo in September, 1977. Commissioned an Ensign in the United States Navy in July, 1977, he presently holds the rank of Lieutenant. Married to the former Holly Edwards of New Berlin, New York, they have three childres: Brie Alexandra (May, 1978) Wesley Adam (October 1980) and Eric Christian (October, 1980). In January, 1981, he entered the Graduate School of the University of Texas.

Permanent address: 31 Genesee St.
New Berlin, New York

Appendix 4-9

Pressure Effects of the Static Mud Column in Abandoned Wells
(Johnston and Knape, 1986)

LP 86-06

Pressure Effects of the Static Mud Column in Abandoned Wells

Texas Water Commission

September 1986

PRESSURE EFFECTS OF THE STATIC MUD COLUMN IN ABANDONED WELLS

By

Orville C. Johnston and Ben K. Knape

LP 86-06

Texas Water Commission

September, 1986

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ABSTRACT

The objective of this research is to establish a reference framework (with respect to concepts, safety factors, etc.) concerning the status and condition of abandoned wells which may be located near an injection well operation. The validity of the assumption of a wellbore filled with mud of a minimum weight of 9 pounds per gallon for abandoned wells is confirmed through a survey of the literature and interviews of experts in the field. In addition to the resistance to vertical fluid flow in an abandoned well, which is conveyed by the hydrostatic head of 9 pounds per gallon mud, the gel properties of borehole mud alone in a 15-inch diameter wellbore at a 5,000 foot depth, will withstand at least 27.75 psi of reservoir pressure increase from injection. Other intangible safety factors include the following: (a) there is a high probability that wells abandoned after 1967 are properly plugged; and (b) wells abandoned during the period 1919-1967 may be properly plugged, even if documentation is lacking. Experience with well drilling has shown that uncased wells in the Gulf Coast region of Texas, and uncased wells which penetrate certain unstable rock formations of the Triassic System in West Texas, rapidly undergo borehole closure by the natural processes of borehole wall swelling, sloughing, and bridging. This report identifies 267 abandoned wells located near certain industrial waste disposal well sites which are assumed to be plugged with drilling mud only.

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APPENDIX

PRESSURE EFFECTS OF THE STATIC MUD COLUMN IN ABANDONED WELLS

INTRODUCTION

The Texas Water Commission regulates Class I injection wells by permit. The permit process involves review of all artificial penetrations of the subsurface, within a 2.5 mile radius of a proposed injection well, to determine the maximum allowable reservoir pressure build-up without potential for causing fluid movement through abandoned wells. The review process must include consideration of problem wells which are abandoned with inadequate cement plugs or have inadequate or nonexistent plugging records. It has been assumed that such abandoned wells are filled with a 9 pound per gallon mud, unless otherwise documented.

The Commission has assumed in its permit review process, that the total reservoir pressure within the area of influence of an injection well should not exceed the hydrostatic head of the mud column at any unplugged abandoned well within the area. This criterion for safe limits on injection operations does not consider several factors which may add considerably to the safety of an injection operation.

Purpose

The purpose of this investigation is to evaluate the following with respect to artificial penetrations: (a) the history of drilling and plugging practices as they relate to the probability of interformational fluid transfer in abandoned wells; (b) gel strength of wellbore mud; and (c) effects of geologic and geographic differences as determinants of natural borehole closure.

Scope

This study includes the collection and compilation of all available data pertaining to the control of downhole pressure and potential for fluid movement in abandoned wells which are filled with drilling mud. In addition to the resistance to fluid flow conveyed by the weight of the mud column filling an abandoned well, the study will also consider the added pressure effects of the gel strength of drilling mud, the development of well drilling and plugging practices over the years, the probabilities of natural borehole closure, including the geologic determinants on the condition of the abandoned borehole, and the properties of drilling mud in the borehole after long periods of time. The scope of the study has been limited to literature and file research, interviews with persons experienced in well technology, and the preparation of a report which presents tabulated abandoned well data, location maps, and conclusions and recommendations.

Method of Investigation

Following the study proposal, formulated early in 1985, the investigation began in November, 1985, and involved two persons working full time. Persons experienced in the fields of well drilling, plugging procedures, and mud technology were interviewed concerning the ability of mud in abandoned wells to prevent fluid flow. Summaries of these interviews or "personal communications" are included in the Appendix to this report, along with summaries of literature of particular relevance to the study.

The literature review was accomplished by consulting references suggested by the persons interviewed, and by the assistance of the Commission's library staff and the U. S. Environmental Protection Agency (EPA) Region 6 staff in conducting computerized data base searches. The Commission's library staff used the Dialog Information Retrieval Services, Inc. system which has more than 220 available data bases. The four data bases of the Dialog system which contain engineering and geotechnical data were searched by inputting the key word groupings of "abandoned wells," "well plugging," mud-plugged wells," and "mud gel strength," and the various permutations of these groupings into the computer system. Also, a computer search of the National Ground Water Information Center (NGWIC) library files was provided by the EPA Region 6 office. The files or data bases searched are described under the heading of "Data Bases" following the Reference section of this report.

All literature relevant to the study is listed in this report under the heading of "References." Considering the extensive literature search undertaken, it was noted that there are remarkably few references in the literature to the specific topics of this study. Apparently, there have been very few opportunities to gather mud data from abandoned wells, since abandoned wells are seldom reentered. The relatively few known cases of reentering abandoned wells were either: (1) to recomplete the wells for injection operations for wastewater or brine disposal or water flood operations for enhanced recovery of petroleum, (2) excavations in mining operations which encountered abandoned mineral exploration holes, or (3) were ordered by the TWC or its predecessors, or the Railroad Commission of Texas, to properly plug the well to protect ground water or mineral resources.

Following the review of the literature and personal communications, criteria for identifying potentially problem abandoned wells within a 2-1/2 mile radius of an active permitted Class I waste disposal well were formulated. A potential problem well was defined, for the purpose of this study, as an abandoned well which lacked clear documentation of at least one cement plug between the disposal zone (injection formation) and the base of slightly-saline ground water (3,000 mg/l total dissolved solids). Using the criterion described above, potential problem abandoned wells were tabulated by the Commission's Underground Injection Control Section staff from the microfiche and hard copy files of permitted waste disposal wells.

The well tabulation portion of the study (Table 1) is presented alphabetically by waste disposal well permittee and/or site location. Figure 1 shows the sites in Texas of waste disposal well areas of review having one or more potential problem abandoned wells. Figures 2 through 28 show the locations of potential problem abandoned wells within each waste disposal well area of review.

In Table 1, each well is identified by well operator and well name (lease and well number within the lease). Drilling and abandonment dates are included in Table 1 to allow conclusions to be drawn concerning probable well depths, and well construction and plugging technology available at the time the well in question was drilled. Under the column heading of "Remarks," each of the wells compiled in Table 1 is characterized by documentation of wellbore mud, and long-string casing. When available, mud weights are also reported in this same column in pounds per gallon.

Acknowledgements

The principal investigators would like to express appreciation to numerous individuals who assisted in the preparation of this report. In particular, appreciation is expressed to those persons who agreed to be interviewed, as indicated under the description of "Personal Communication" in the References section and in the Appendix to this report. Direct supervision and guidance throughout the project were provided by Bill Klemt, who also reviewed and critiqued the report. We are indebted to many other Commission personnel for review, editing, typing, preparing illustrations, and reproducing the report.

Valuable suggestions for the literature search and on content editing were provided by Rich Wooster of the U. S. Environmental Protection Agency.

HISTORICAL DEVELOPMENT OF DRILLING AND PLUGGING TECHNOLOGY

Drilling

Oil and gas wells that were drilled and abandoned prior to 1930 are probably not much deeper than 3,000 to 4,000 feet (Meers, 1985), (Hellinghausen, 1985), and (Smith, 1981). Data on these early wells is usually difficult to impossible to locate.

Prior to the early 1930's, much of the drilling for oil and gas production utilized cable tools and rotary rigs which were crude compared to today's equipment. The advent of World War II spurred efforts to improve drilling technology. Improvements in materials and computerization have contributed to the development of the sophisticated rotary rigs and drill bits which are available today. With the advances in drilling equipment, well depths have increased significantly so that depths exceeding 25,000 feet can be achieved today.

Coincidentally with rotary rig development, mud technology progressed from an art to a science. In contrast to cable tool drilling which did not employ drilling fluid systems (Davis, 1985 personal communication), rotary drilling requires drilling fluid to remove cuttings from the hole, to control pressure surges, to promote borehole stability, and to cool and lubricate the bit. In the early days of rotary drilling, drilling fluid was mostly water which when mixed with drill cuttings, resulted in "drilling mud" (Smith, 1985). Most early wells drilled by rotary techniques are therefore considered to have been drilled with "native muds" derived from the clay formations penetrated by the drill bit. Water had to be continually added to thin native muds, and the minimum weight for these drilling muds probably was not less than 9 pounds per gallon (Cox, 1986), (Davis, 1985), and (Marr, 1985). During the 1930's, bentonite and barite additives were first used to improve mud stability and increase mud weight for improved pressure control (Smith, 1985) and (Marr, 1985). Since that time, numerous service companies and research facilities have been established to provide personnel and technology necessary to control mud properties during a drilling operation. These properties include but are not limited to viscosity, gel strength, mud weight, and stability.

Plugging and Abandonment

Little thought was given to well abandonment in the early days of oil well drilling and production. Undoubtedly, many early wells which proved to be dry holes or which produced for a time before becoming inactive, were simply abandoned without any special closure procedures, either out of being unaware of any possible adverse environmental consequences of such actions, out of negligence, or out of being unwilling or unable to spend the necessary funds for plugging. Rotary drilled "dry holes" can be safely assumed to have been left full of mud as a minimum condition, because such wells are drilled, logged, and tested with mud in the wellbore, and there would be no economic reason to evacuate the hole of drilling mud prior to abandonment. Regarding abandonment of producing wells without filling the casing with mud, the Texas Water Commission and its predecessors have consistently not permitted waste disposal well completions in areas of a formation known to produce oil or gas. It is therefore unlikely that an inadequately plugged production well will lie within the area of influence of a permitted waste disposal well.

Some early attempts at plugging wells involved only driving a wooden plug into the well casing head. Over the years, abandoned wells have commonly had all sorts of unwanted debris thrown into the open well casings. The materials discarded into abandoned wells commonly included drilling site debris, scrap lumber, and metallic junk including broken tools. The modern practice of filling an abandoned well with mud and spotting cement plugs in the well has developed to meet the objective of confining all native fluids to the formations in which they were encountered. In leaving the wellbore full of mud, however, probably very little consideration has been given to possible circumstances such as (1) partial mud loss to "lost circulation" or "thief" zones in the subsurface, or (2) decrease in mud column height from removal of casing for salvage. Consequently, calculations of mud hydrostatic head in an abandoned well should take into account the possibility of incomplete filling of the hole from known lost circulation zones or other circumstances documented in records of the well.

The State of Texas has recognized the need for proper plugging of abandoned wells since 1899 (House Bill 542, 1899). The 1899 legislation calling for plugging of abandoned wells, however, did not designate to a particular branch of state government the regulatory and enforcement authority of this law.

In 1919, Senate Bill 350 gave the Railroad Commission of Texas (RRC) regulatory responsibility for proper well plugging. Current plugging regulations are detailed in Rule 14 of the Texas Railroad Commission, which was adopted on January 1, 1967. Rule 14 requires that abandoned wells be properly plugged with a specified combination of cement plugs and mud-laden fluid weighing at least 9.5 pounds per gallon, to confine oil, gas, or water to the strata in which they naturally occur. Rule 14 also requires that a well operator notify the Railroad Commission and all offset landowners and well operators of the intent to plug. Under Rule 14, the Railroad Commission reviews plugging plans for adequacy, requiring modifications to the plans as necessary to protect reserves of oil, gas, and water. According to Rule 14, plugging must commence in a well within one year of the end of drilling or production operations. Extensions of the maximum time period before commencing plugging operations may be granted by the Railroad Commission, provided that there is no pollution hazard, and provided there is adequate financial assurance in place to pay for well plugging without the expenditure of State funds. Noncompliance with Railroad Commission plugging rules subjects well operators to both civil and administrative fines. To remedy the problem of specific improperly abandoned wells in cases where the operator is unknown or financially insolvent, the Railroad Commission also administers a program which has plugged approximately 1400 such wells since 1965, using state funds.

MUD GEL STRENGTH

Most wells drilled for oil and gas use water-based drilling fluids which contain the native earth solids and rock cuttings acquired while drilling, and commercially available drilling mud additives. When a mud mix is allowed to remain quiescent for a period of time, a gel develops. Laboratory data acquired over relatively short intervals indicates that gel strength increases with time. Until the gel structure is broken, the mud will not be displaced. The pressure increase required to displace gelled mud can be significantly large and will often be a major factor in controlling fluid flow from a waste disposal formation.

The plastic flow of clay suspensions is well known. Gel strength data presented by (Garrison, 1938) indicates the strengths increase more rapidly at first, and then gradually approach a constant value as time passes. The reaction time follows a rather simple equation:

$$S = \frac{S'Kt}{1 + Kt}$$

where S' = gel strength after a long time
K = rate constant
t = time
S = gel strength at t

The equation may be rearranged so that a linear relationship exists between t/S and time.

The relationship can be expressed in the following equation:

$$\frac{t}{S} = \frac{1}{S'K} + \frac{t}{S'}$$

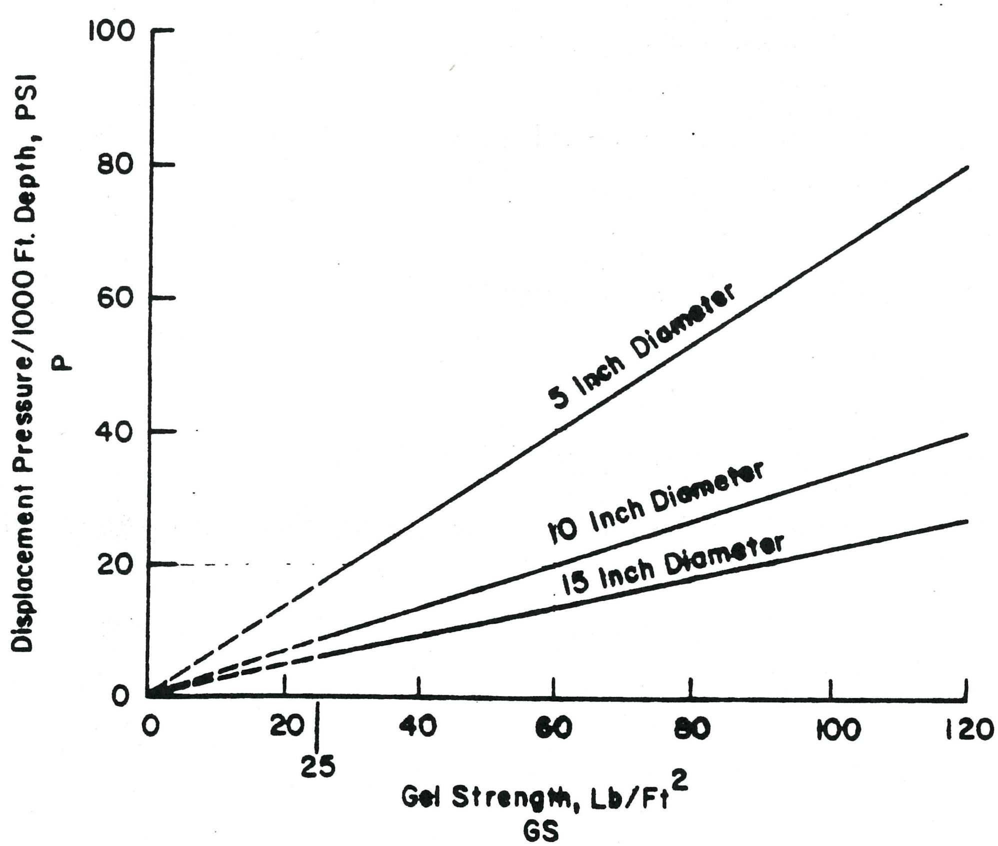
Based on limited data, drilling mud gel strengths ranging from 25 to 120 pounds per 100 square feet have been noted (Barker, 1981). When evaluating the effect of a mug plug on confining fluids in a reservoir, the most conservative value (or lowest gel strength) should be used to avoid an over optimistic estimate of the mud displacement pressure.

In addition to the pressure required to overcome the hydrostatic head of the borehold mud, the pressure necessary to displace the mud plug varies directly with the gel strength and well depth and inversely with borehole diameter (Barker, 1981) as follows:

$$P = \frac{0.00333\ (GS)(h)}{D}$$

where GS = gel strength, pounds/100 feet^2
h = height of mud column or depth of well, feet
D = hole diameter, inches
P = displacement pressure, psi

Displacement pressures based on gel strengths for hole diameters of 5, 10, and 15 inches are shown in graph form below:



Gel strengths of mud left in abandoned wells are generally unknown. The data cited above indicate that a mud plug with a gel strength of 25 pounds/100 feet^2, in a 5,000 foot deep well of 15-inch diameter should be capable of restricting a pressure difference of at least 27.75 psi. This is a relatively minor pressure restriction which should be regarded as a safety factor and not considered when developing operating parameters that would be acceptable for an injection well. It should be noted that drilling muds with high gel strengths (exceeding 100 pounds/100ft^2) would have a significant displacement pressure in abandoned wells 5000 feet or more in depth.

NATURAL BOREHOLE CLOSURE

Geologic factors such as sediment consolidation (cementation) and mineralogy are major determinants of the probability of natural borehole closure. These geologic factors are found to vary geographically throughout the State. Older sediments characteristic of West Texas are generally more consolidated, and uncased wellbores in that area are less prone to seal over by caving or sloughing of the wellbore walls (Marr, 1985), (Meers, 1985), (Johnson, 1985), (Davis, 1985), and (Kent and Bentley, 1985). Abandoned wells have been reentered and cleaned out for reuse after many years of dormancy in West Texas by merely washing out the wellbore mud with a drill bit (Marr, 1985).

In contast, the geologically young and unconsolidated sediments of the Gulf Coast tend to slough and swell, and an uncased well in that region commonly will squeeze shut within a matter of hours. Well bores have closed in while changing bits or running casing. Drillers sometimes have difficulty in finding and following the original wellbore when reentering and redrilling abandoned wells and attribute this problem to the natural healing of the sediments originally penetrated (Meers, 1985) and (Hellinghausen, 1985).

Most of the State's permitted industrial waste disposal wells are located on the Gulf Coast and in West Texas. Information gathered from literature and communications from experienced field personnel confirm the validity of characterizing these two regions of the State as one where natural closure of the boreholes probably occurs (Gulf Coast) versus one where boreholes may be stable and remain open for an extended time (West Texas).

A major exception to the normal stability of West Texas boreholes, however, is exhibited in uncased sections of wells penetrating certain shale formations of Triassic age. This phenomenon is typical below the base of the surface casing in a well with the long-string casing absent, because of never having been installed, or having been pulled from the well for salvage prior to abandonment. The Triassic formations which contribute to wellbore instability are generally referred to by drillers as "red beds." These beds consist largely of water-sensitive clays which swell and slough in a borehole, causing problems with the sticking of drill pipe and casing during well construction, and total hole closure during and after well abandonment.

ANALYSIS OF ARTIFICIAL PENETRATIONS

The 267 wells in Table 1 represent the results of the survey of Texas Water Commission files to locate all abandoned wells which (1) penetrate a disposal zone within 2-1/2 miles of an active waste disposal well, and (2) lack clear documentation of proper plugging with cement to isolate wastes injected into strata containing ground water of more than 10,000 mg/l total dissolved solids, from strata containing ground water of less than 3,000 mg/l total dissolved solids. This study has attempted to determine if these 267 abandoned wells (Table 1) pose a problem in being potential avenues of fluid movement between formations because of elevated reservoir pressures resulting from injection operations.

Sixteen (16) of the 267 abandoned wells in Table 1 were plugged after the 1967 adoption of Rule 14 by the Railroad Commission of Texas, and may therefore be assumed to be plugged in a manner which will prevent interformational transfer of fluids. Rule 14 standardized plugging procedures in all Railroad Commission districts in Texas, many of which procedures had long been required at the discretion of the various district supervisors. Implementation of Rule 14 also insured that abandoned wells are plugged within one year following the cessation of drilling or production operations, unless the Railroad Commission has granted an extension of this time period conditioned upon there being no pollution hazard and no risk of State funds for plugging the well.

Of the 251 wells in Table 1 which were abandoned prior to the adoption of Railroad Commission Rule 14, 238 are shown by available records to be Gulf Coast wells without long-string casing. Uncased wells in the Gulf Coast region are not considered to pose a problem to waste disposal well operations because of the high probability of natural borehole closure, which is a property of the unconsolidated sediments characteristic of that region of the State.

The remaining 13 wells in Table 1 which were abandoned prior to adoption of Rule 14 are assumed to have boreholes intact by reason of (1) full hole casing, or (2) consolidated host sediments. In regions such as West Texas, which are characterized by hard consolidated sediments, it has been determined that boreholes may remain open for several decades without casing. Each of these remaining 13 abandoned wells in Table 1 has been evaluated in the waste disposal well permitting process to confirm that the pressure build-up at the abandoned well, resulting from injection into the nearby waste disposal well, will be less than the hydrostatic head of 9 pound per gallon mud filling the abandoned well.

Additional factors which may add significantly to the safety of mud plugs in abandoned wells where documentation of the proper cement plugs is lacking include the following:

(1) Whereas Railroad Commission Rule 14 represented primarily a refinement and standardization of existing plugging practices, many wells which were abandoned before 1967 were properly plugged with cement, even if full documentation is lacking. The problem of inadequate documentation for abandoned wells includes circumstances ranging from failure to file the proper well records, to administrative problems in processing and storing records. Indeed, many instances of inadequate documentation are the result of well records having been rendered illegible by photocopying and microfilm reduction.

(2) Because of the limitation of early drilling technology, many wells drilled prior to 1930 will not penetrate to depths of modern waste disposal well injection zones.

(3) Mud gel strength increases the pressure required to displace the hydrostatic column of wellbore mud from an abandoned well.

(4) Triassic "red beds" in West Texas exhibit the property of natural borehole closure in uncased intervals of a well. It is therefore a possibility that an abandoned well with incomplete documentation in West Texas will be naturally sealed if the well was left with no casing through an interval of "red beds."

CONCLUSIONS

1. Wells that were abandoned during the period 1919-1967 may be properly plugged even if documentation is lacking, and there is a very high probability that all wells abandoned after 1967 are properly plugged.

2. Abandoned uncased wells in the Gulf Coast region of Texas and in Triassic "red beds" of West Texas rapidly undergo borehole closure by the natural processes of unstable formations.

3. Abandoned uncased wells in consolidated hard rocks may remain open and stable over time ranging from years to several decades.

4. In the absence of cement plugs in an abandoned well near injection operations, the wellbore mud will resist vertical fluid movement to the degree to which the sum of the mud hydrostatic head, mud gel strength, and borehole restrictions exceed the formation pressure of the injection zone.

5. Mud company lab data indicate that mud gel strength increases with time and temperature. In the general absence of mud gel strength data for abandoned wells, a minimum gel strength of 25 lb/100 ft^2 can be conservatively assumed.

6. Calculations of mud hydrostatic head in an abandoned well should take into account the possiblity of incomplete filling of the hole due to known lost circulation zones, or other circumstances documented in the operating records of the well.

7. A search of the Commission's waste disposal well files has identified 267 abandoned wells (Table 1) that were considered to be incompletely plugged or of uncertain plugging status, because cement plugs could not be documented between the injection zone (with groundwater of 10,000 mg/l or greater, total dissolved solids) and the base of fresh to slightly-saline ground water (3,000 mg/l or less, total dissolved solids). These 267 abandoned wells are distributed between 38 of the 53 active industrial or commercial waste disposal well operations (sites) in Texas. None of these abandoned wells are considered to pose a problem of interformational fluid flow.

RECOMMENDATIONS

Conditional upon available funding, a second phase of study should be carried out consisting of laboratory and field investigations to verify the conclusions of this initial phase of the study. The laboratory study should determine the effect of temperature, time, pressure, and composition on mud gel strength. The field investigations should consist of re-entering selected mud-filled abandoned wells in the Gulf Coast and West Texas regions to determine mud conditions and to look for evidence of fluid movement up the wellbore. Finally, this proposed second phase of work should include the drilling of test holes in the immediate vicinity of selected abandoned wells for the purpose of reservoir pressure monitoring.

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DATA BASES

COMPENDEX

1970-present, 1,415,000 records, monthly updates (Engineering Information, Inc., New York, NY).

The COMPENDEX data base is the machine readable version of the Engineering Index (Monthly/Annual), which provides abstracted information from the world's significant engineering and technological literature. The COMPENDEX data base provides worldwide coverage of approximately 3500 journals and selected government reports and books.

GEOREF

1919-present (North American material), 1967-present (worldwide material), 1,005,000 records, monthly updates (American Geological Institute, Falls Church, VA).

GEOREF provides comprehensive access to more than 4,500 international journals, plus books, conference papers, government publications, dissertations, theses, and maps concerned with all aspects of geology, geochemistry, geophysics, mineralogy, paleontology, petrology, and seismology. Approximately 40% of the indexed publications originate in the U.S. and the remainder from outside the U.S. Publications of international organizations make up about 7% of GEOREF.

NGWIC DATA BASE

Computerized bibliographic ground water data base featuring nearly 50,000 documents, indexed by more than 700 hydrogeologic descriptions and virtually any relevant aquifer geographic, chemical, biologic, and reference term. The National Ground Water Information Center (NGWIC) is funded in part by the U.S. EPA and is managed by the National Water Well Associaiton (NWWA). The NGWIC DATA BASE has recently changed its name and address to GROUND WATER ON-LINE, NGWIC, 6375 Riverside Drive, Dublin, Ohio 43017.

NTIS

1964-present, 1,122,000 records, biweekly updates (National Technical Information Service, NTIS, U.S. Department of Commerce, Springfield, VA).

The NTIS data base consists of government-sponsored research, development, and engineering, plus analyses prepared by federal agencies, their contractors or grantees. It is the means through which unclassified, publicly available, unlimited distribution reports are made available for sale from such agencies as NASA, DDC, DOE, HHS (formerly HEW), HUD, DOT, Department of Commerce, and some 240 other units. State and local government agencies are now beginning to contribute their reports to the file.

The NTIS data base includes material from both the hard and soft sciences, including substantial material on technological applications, business procedures, and regulatory matters. Many topics of immediate broad interest are included, such as environmental pollution and control, energy conversion, technology transfer, behavior/societal problems, urban and regional planning.

WATER RESOURCES ABSTRACTS

1968-present, 176,000 records, monthly updates (U.S. Dept. of the Interior, Washington, D.C.).

WATER RESOURCES ABSTRACTS is prepared from materials collected by over 50 water research centers and institutes in the United States. The file covers a wide range of water resource topics including water resource economics, ground and surface water hydrology, metropolitan water resources planning and management, and water-related aspects of nuclear radiation and safety. The collection is particularly strong in the literature on water planning (demand, economics, cost allocations), water cycle (precipitation, snow, ground water, lakes, erosion, etc.), and water quality (pollution, waste treatment).

WRA covers predominantly English-language materials and includes monographs, journal articles, reports, patents, and conference proceedings.

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water

Remarks: [1]Indicates inadequate documentation of proper construction and abandonment.
[2]Indicates abandoned with mud in hole but lacking documentation of proper cement plugs.
[3]Indicates long string casing in hole below surface casing.
Mud weights in pounds per gallon are indicated thusly, [9.5 lb/gal].
Disposal zone depths in feet below land surface are indicated thusly, DZD 4,900 Feet.

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
Cecos International Odessa Plant, Ector Co. DZD 4,900 Feet WDW-146	1	Gulf Oil	CT-1	—	1956	1
Celanese Chemical Co. Bay City Plant, Matagorda Co. DZD 3,300 Feet WDW-14, 32, 49, 110	2	United N & S	Wendl, et al. No. 1	1942	1952	2, 3
	3	do	Dowdy No. 1	—	1944	1
	4	do	Lambert No. 1	—	1952	2, 3
	5	do	Stoddard No. 7	1942	1952	2, 3
	6	do	Pierce Est. No. 1	1954	—	2, 3
Bishop Plant, Nueces Co. DZD 4,200 Feet WDW-210, 212	7	Hooser	L. Davis No. 1	—	—	1
	8	Haynes & U. T. Drill	O. Janke No. 2	1963	—	1
	9	Humble Oil	King Ranch-Big Cesar No. 3	—	1966	1
Clear Lake Plant, Harris Co. DZD 4,600 Feet WDW-33, 45	10	Exxon	Humble-West Fee "C" 4	1939	1939	2
	11	do	Humble-West Fee "C" 45	1940	1948	2
	12	do	Humble-West Fee "C" 43	1940	1940	2
	13	do	Humble-West Fee "C" 3	1939	1963	2
	14	do	Humble-West Fee "C" 32	1940	1972	2
	15	do	Humble-West Fee "C" 58	1940	—	1
	16	do	Humble-West Fee "C" 2	1938	1939	2

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
Celanese Chemical Co.						
Clear Lake Plant, Harris Co.	17	Exxon	Humble-West Fee "C" 12	1939	1970	2
	18	do	Humble-West Fee "C" 54	1940	1940	2
	19	do	Humble-West Fee "C" 50	1940	1940	2
	20	do	Humble-West Fee "C" 1	1964	—	2
	21	do	Humble-West Fee "C" 62	1957	1957	2
Chemical Waste Management Corpus Christi Plant, Nueces Co. DZD 3,470 Feet WDW-70	22	Ivan J. Allen	Agnes Jurica, et al. No. 1	—	1966	2
	23	Seaboard Oil	Ed Jurica, et al. No. 1	1937	1937	2
	24	Ben D. Marks	Lockett No. 1	1950	1950	2
	25	Texas Southern Oil & Gas	N. V. Rambo No. 1	—	1954	2
	26	Mariss, Weisman & Train	Joe Hroch No. 1	1950	1950	2
	27	Black & Steven	Jochete No. 1	—	1965	2
	28	Ed M. Jones	Lucy F. Cooke No. 1	—	—	1
	29	C. A. Black, Jr.	Petty No. 1	—	1964	2
	30	Sam Wilson	Herold No. 1	1937	1937	2
	31	Jack L. Hamon	W. T. Pulliman No. 1	1967	1968	2
	32	S. H. Powell & S. W. Corporation	Albeta Zolansky No. 1	—	1955	2
	33	Appel Petroleum	Lamar Folda No. 1	—	1958	2
	34	W. R. Lloyd	Jacob Nemce No. 1	—	1960	2
	35	W. E. Fox, Trust	R. N. O'Neil No. 1	1950	1950	2
	36	Graham & Waldron	Singer No. 1	1941	1941	1
	37	Arnold Well Service & Morgan	C. T. Richardson No. 1	—	1956	2
	38	Howell	Merriman No. 1	—	—	1
	39	C. C. Winn	Dane Lamar Smith No. 1	—	1960	2
	40	do	F. V. Arvin No. 1	—	1960	1
	41	Strike Resources	Sun Kosar No. 1	—	—	1
	42	Sun Oil	W. S. Kirkpatrick No. 1	1972	1972	2
	43	Knox Industries	Holly No. 1	—	—	1

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
Chemical Waste Management						
Corpus Christi Plant, Nueces Co.	44	Coquina Oil	Valka No. 1	—	—	1
	45	Train-Wiseman	Ed Jurica Ent. No. 1	1950	1951	1
	46	Coastal States Gas	Pauline Kraft No. 1	1971	1971	2
	47	Canus Petroleum	F. Evans Gas Unit No. 1	1977	1981	2
	48	R. L. Siboal	Batek No. 1	—	—	1
	49	Aminol USA	Kureska No. 1	—	—	1
	50	McFarland	J. Houch No. 1	—	—	1
	51	Nor-Am Petroleum	Peterson Prop. No. 1	—	—	1
	52	W. B. Dansfield	Holly No. 1	—	—	1
	53	Winn	London No. 1	—	—	1
	54	Graham	Lear No. 1	—	—	1
	55	Cox	Fitzpatrick No. 1	—	—	1
	56	Kelly-Bell	Baldwin Farms "G" No. 1	—	—	1
	57	Canus Petroleum	Edwards No. 1	—	—	1
	58	McFarland	Jurica No. 1	—	—	1
	59	Marks	Houch No. 1	—	—	1
	60	Knox Industries	Peterson Properties No. 1	—	—	1
	61	Geodominion Petroleum	Irma R. Petty No. 1	1984	1984	2
	62	D. H. Geiser	L. P. Cook Est. No. 1	—	—	1
	63	R. C. Hagens	Behman Brothers Foundation No. 1	—	—	1
	64	Cenergy Exploration	Ennis Johnson No. 1	—	—	1
Corpus Christi Petrochemical Co. Robstown Plant, Nueces Co. DZD 7,130 Feet WDW-152, 153	65	Renwar Oil	C. Harrington No. 1	1938	—	1
	66	do	C. Harrington No. 2	1938	—	1

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
DUMAS AREA						
Diamond Shamrock Corporation						
Dumas Plant, Moore Co.						
DZD 1,106 Feet						
WDW-102, 192, 225, 226						
Lundberg Industries, Ltd.						
Dumas Plant, Moore Co.						
DZD 1,125 Feet						
WDW-3	67	Diamond Shamrock	W. W. Burnett No. 1	1932	1932	2
	68	Shamrock Oil	Coffee No. 1	1931	1936	1
	69	do	M. Johnson No. 1	1941	—	1
	70	do	Luckhardt No. 1	1941	1965	1
	71	Gulf Oil & Phillips Petroleum	Fisher No. 2	—	—	2
	72	Shamrock Oil	Brumley No. 5	—	1966	2
E. I. DuPont De Nemours & Co.						
Corpus Christi Plant, San Patricio Co.						
DZD 4,050 Feet						
WDW-109, 121	73	A. L. Bob	J. Green Est. No. 2	1938	1938	1
	74	Eleanor Oil	J. Green Est. No. 1	1937	1937	1 [9.8 lb/gal]
	75	Hooper Rutherford	J. D. & Edith Willis No. 1	—	—	1
	76	Eleanor Oil	W. Kline No. 1	1936	1936	1
La Porte Plant, Harris Co.						
DZD 4,800 Feet						
WDW-82, 83, 149	77	Gulf Oil	Texas State (30413) No. 3	1963	1963	2
	78	do	Texas State (30413) No. 2	—	—	1
	79	do	Texas State (30413) No. 1	—	—	2

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
E. I. DuPont De Nemours & Co.						
La Porte Plant, Harris Co.	80	Humble Oil & Refining Co.	Hog Island Fee (01796) No. 1	—	—	1
	81	Crown Central Petrochemical	Eugene Bray, et al. No. 1	1961	1961	1
	82	Copeland Oil	Robert Stateland No. 1	—	—	1
	83	Slater, Williamson, & Hughes	C. M. Morris No. 1	1966	1966	2
	84	Turnbull & Irwin	Helen Dunn No. 1	1934	1934	2
	85	Gidden & Shriver	W. D. Sutherland, et al. No. 1	—	—	1
	86	Humble Oil	S. A. Girard & C. A. Bryan No. 1	—	—	1
	87	Amerada Petroleum, or Humble Oil	Unknown	—	—	1
	88	Amerada Petroleum	Unknown	—	—	1
	89	W. D. Fitzgerald	E. K. Gray	—	—	1
	90	Melba Oil Co.	Humble Oil	—	—	1
	91	J. R. Copeland	Humble Oil, et al. No. 1	—	—	1
Sabine Riverworks, Orange Co. DZD 4,300 Feet WDW-54, 55, 56, 57, 132, 191, 207	92	J. R. Neal	L. Neal No. 1	—	1971	1
	93	Wells, Trustee	W. Stark No. 1	1927	1927	1
	94	do	H. W. Stark No. 1	1927	1927	1
	95	do	H. W. Stark No. 1	1927	1927	1
Victoria Plant, Victoria Co. DZD 3,000 Feet WDW-4, 28, 29, 30, 105, 106 142, 143 144, 145	96	Renwar Oil	J. Weaver No. 1	1939	—	2
	97	Bridwell Oil	T. Fromme No. 1	1948	—	2
	98	Guadalupe Valley Oil	Santa Claus No. 1	—	—	—
	99	do	J. Weaver No. 1	1920	—	1

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps		Operator	Well Name	Date Drilled	Date Plugged	Remarks
E. I. DuPont De Nemours & Co. Victoria Plant, Victoria Co.	100	6	Birdwell Oil	B. Spies No. 1	1944	—	1
	101	11	Renwar Oil	M. Stoner No. 1	1938 1939	—	2
	102	17	Birdwell Oil	J. Whitney No. 1	1943	—	2
	103	19	C. Dunwoody, Jr.	H. Smith Est. No. 1	1953	—	2
	104	20	Pontail Refining	F. Bowman No. 1	1948	—	2
	105	21	Pontail Refining	F. Bowman No. 1A	1948	—	2
	106	22	Monday Oil	C. Stubblefield No. 1	1948	—	2
	107	24	Billy Birdwell et al.	R. Diebel No. 1	1949	—	2
	108	31	Randerson & Head	Rydolph & Smolik No. 1	1950	—	2
	109	32	Continental Oil	W. Maroney No. 1	1943	—	2
	110	37	R. S. Renderson	H. Stubblefield No. 1	1950	—	2
	111	59	W. G. Dorsey, Jr.	E. Rydolph No. 1	1949	—	1
	112	40	R. N. Ranger	W. Krahl No. 1	1952	—	1
	113	41	Union Production	Rydolph No. A-1	1950	—	2
	114	42	RBJ Company not drilled	Rydolph No. 1-M	1969	—	1
	115		Continental Oil mapping error	P. Rydolph No. ?	—	—	1
	116		E. I. DuPont inj. well	E. I. DuPont No. 1	—	—	1
Everest Minerals Corporation Hobson Mine, Karnes Co. DZD 5,610 Feet WDW-168	117		Standard	Pollok No. 1	—	—	1
	118		Bright & Schiff	Foegelle No. 1	—	—	1
	119		Mayo	Moczygamba No. 1	—	—	1
GAF Corporation Texas City Plant, Galveston Co. DZD 3,550 Feet WDW-34, 113, 114	120		Midstates	J. Braun No. 1	1950	—	1
	121		Pan American Oil	C. Martin No. 1	1954	—	1
	122		Humble Oil	D. S. Monen No. 3	1938	—	1
	123		Pan American Oil	J. N. Fream No. 5	—	—	1

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
HEBBRONVILLE AREA						
Caithness Mining Corporation McBride Mine, Duval Co. DZD 4,100 Feet WDW-185						
Conoco, Incorporated Trevino Mine, Duval Co. DZD 3,800 Feet WDW-189						
Everest Minerals Corporation Las Palmas Mine, Duval Co. DZD 4,250 Feet WDW-187	124	Massingale & Rife	Benavides No. 1	1947	1947	2 [8.4 lb/gal]
	125	Hamon & Cox	Taylor No. 1	1950	1950	2 [10.1 lb/gal]
	126	Dan Auld	Taylor No. 2	—	—	2 [9.8 lb/gal]
	127	Hamon & Cox	Taylor No. 1-A	1952	1952	2 [10.3 lb/gal]
	128	Ben Marks	Gruy No. 1	1950	1950	2 [10.8 lb/gal]
	129	do	Gruy No. 2	1950	1950	2 [10.8 lb/gal]
	130	Killam & Hurd	Gruy No. 5	1958	1958	2 [9.9 lb/gal]
	131	Hewit & Dougherty	Gruy No. 1	1948	1948	2 [10.2 lb/gal]
	132	Morris Cannon	Gruy No. 4	1950	1950	2 [9.8 lb/gal]
	133	Southern Minerals	Silver Lake Ranch No. 1	1951	1951	2 [10.0 lb/gal]
	134	Ben Marks	Gruy No. 3	1951	1951	2
	135	Killam & Hurd	Gruy No. 6	1955	1955	2
	136	Rand Morgan	Gruy No. 1	—	—	2
	137	Valor Oil	Trevino No. 1	—	—	2
	138	Henshaw Brothers	Alonzo Taylor No. 1	1955	1955	2
	139	C. S. Sellars	do	1945	1945	2
	140	T. S. West	J. T. Rogers No. 1	—	—	2
	141	Chicago Company	Trevino No. 1	1951	1951	2
	142	John F. Camp	G. B. Buesher No. 1	1946	1946	2
	143	C. G. Classcock	J. Dunn No. 1	1952	1952	2

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
HEBBRONVILLE AREA						
	144	Caroline Hunt Trust	E. Miller No. 1	1948	1948	2
	145	Trio Oil	E. S. Miller No. 1	1949	1949	2
	146	John F. Camp	Dunn Ranch B-1	1947	1947	2
	147	H. J. Porter	Sadie Hay No. 1	1943	1943	2
	148	La Gloria	T. B. Miller No. 1	1931	1931	2
	149	Southern Minerals	S. A. Loan & Trust	1951	1951	2
HOUSTON SHIP CHANNEL AREA						
Disposal Systems, Inc. Houston Plant, Harris Co. DZD 6,800 Feet WDW-169						
Empak, Inc. Houston Plant, Harris Co. DZD 6,800 Feet WDW-157						
W. R. Grace & Co. Houston Plant, Harris Co. DZD 6,600 Feet WDW-222, 223						
Merichem Co. Haden Road Plant, Harris Co. DZD 6,400 Feet WDW-147						
Shell Chemical Co. Deer Park Plant, Harris Co. DZD 6,800 Feet WDW-172, 173	150	J. W. Frazier	Houston Deepwater No. 1	—	1938	1
	151	McCormick	Greens Bayou Homesite No. 1	—	—	1 [9.6 lb/gal]

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
HOUSTON SHIP CHANNEL AREA						
	152	Turnbull & Irwin	R. Brooks Est. No. 1	—	—	1
	153	Housch & Thompson	Hine No. 1	—	—	1
	154	Frazier & Brunte	Houston Deepwater No. 2	—	1938	—
	155	Jack Frazier	Jones No. 1	—	1946	—
	156	Cockburn	Brooks Est. No. 1	—	—	—
	157	Amerada Petroleum	Esperson No. 1	1936	—	—
	158	Cockburn Oil	Hines No. 1	1935	—	—
	159	T. S. & F.	Hines No. 2	—	—	—
	160	Giddens & Shiver	Sutherland et al. No. 1	1952	—	—
	161	N. B. Hunt	L. H. Curtin No. 1	1952	—	—
	162	Irwin & Buck	J. B. Hine No. 1	1949	—	—
	163	Miller	Fee No. 1	1926	—	—
	164	do	Fee No. 2	—	—	—
	165	Olympia Oil & Gas	Miller No. 1	1954	—	1
	166	do	Miller No. 2	1954	—	1
	167	Cockburn et al.	White No. 1	1937	—	1
	168	Strang	Goode No. 1	—	—	1
	169	Turnbow	Miller No. 1	—	—	1
	170	West Production	A. Underwood No. 1	1937	—	1
	171	Wolfe	Trichelle No. 1	1952	—	2 [10.2 lb/gal]
	172	Inexco	Kelly-Brock No. 1	—	—	1
I. E. C. Corporation Lamprecht Mine, Liveoak Co. DZD 6,200 Feet WDW-156	173	Herman Brown	Wieding No. 1	1946	1946	1
	174	Kirkwood	W. W. Goebel No. 3	—	—	1
Zamzow Mine, Liveoak Co. DZD 3,050 Feet WDW-159	175	Coquat	W. W. Goebels No. 1	1931	—	1
	176	Ohio Fuel	Goebels No. 1	1937	1937	1

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
I. E. C. Corporation						
Zamzow Mine, Live Oak Co.	177	Phillips Petroleum	W. W. Goebels No. 1	—	—	1
	178	do	do	—	—	1
Lyondell Petrochemical Company Channelview Plant, Harris Co. DZD 4,900 Feet						
WDW-36, 148, 162	179	J. Frazier	Lang No. 1	—	1938	1
	180	do	Hornberger No. 1	—	1938	1
	181	W. Thompson	H. Johnson No. 1	—	—	1
	182	Circle W. Oil	Houston Realty No. 1	1936	—	1
	183	W. M. Hobson	Highland Farms No. 1	—	—	1
	184	O & G Corporation of America	R. Weiss No. 1	—	1959	2
Mobil Oil Corporation Holiday-El Mesquite Plant, Webb Co. DZD 3,550 Feet						
WDW-150, 151, 199	185	B. C. Graham	Benavides B-1	1948	1948	2 [10.2 lb/gal]
	186	Hamill & Smith	J. Benavides No. 1	1936	—	1
	187	Texon Royalty	S. Benavides No. 2	1947	1947	2 [10 lb/gal]
	188	do	S. Benavides No. 1	1947	1947	2 [10 lb/gal]
	189	Magnolia Petroleum	Benavides No. 1	1940	1940	2 [9.6 lb/gal]
	190	do	J. Benavides No. 8	1937	1937	2 [10.6 lb/gal]
	191	United Production	Benavides No. 5	—	—	1
	192	Otis Phillips	Martin No. 1-B	1936	1936	2
	193	Cole Petroleum	R. Benavides No. 69	1930	1930	2
	194	do	R. Benavides No. 75	—	1932	2
	195	E. L. Cox	Benavides No. C-1	1955	1955	2 [10.0 lb/gal]
	196	C. H. Lewis	R. Benavides No. 1	1943	1943	2 [9.9 lb/gal]
	197	Cole Petroleum	R. Benavides No. 68	—	1930	2

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
Monsanto Chemical Company						
Chocolate Bayou Plant, Brazoria Co.						
DZD 4,987 Feet						
WDW-2, 13	198	Phillips Petroleum	Houston "S" No. 1-S	1952	1968	2
	199	Texas Company	Houston Farms Development Company No. 2	1955	1955	2
	200	Phillips Petroleum	Houston "X" No. 1	1954	1959	2
	201	do	Houston "AA" No. 1	1956	1957	2
Penwalt Corporation						
Crosby Plant, Harris Co.						
DZD 6,000 Feet						
WDW-122	202	Moody	E. Cook No. 1	1928	1928	1
	203	Brewster	Kratley No. 1	1954	1954	2 [10.2 lb/gal]
	204	General Crude	Garth No. 1	1952	1952	2 [11.2 lb/gal]
Tenneco Uranium						
W. Cole Mine, Webb Co.						
DZD 5,650 Feet						
WDW-195	205	Piney Point	Cuellar No. 1	1964	1964	2
	206	Flournoy	Benavides No. 1	1965	1965	2
	207	DDG	Benavides No. A-1	1960	1960	2
	208	DDG & Amerada	Benavides No. 1	1959	1959	2
	209	Killum & Hurd	Valdez No. 1-754	1973	1973	2
	210	Naring	Cuellar No. 1	1951	1951	2

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
TEXAS CITY AREA						
Amoco						
Texas City Plant, Galveston Co.						
DZD 5,830 Feet						
WDW-80, 127, 128, 214						
Malone Service Company						
Malone Plant, Galveston Co.						
DZD 3,800 Feet						
WDW-73, 138						
Monsanto Company						
Texas City Plant, Galveston Co.						
DZD 5,000 Feet						
WDW-91, 196						
Textin, Inc.						
Texas City Plant, Galveston Co.						
DZD 5,600 Feet						
WDW-237	211	Stephens	Ruggles No. 1	1950	1950	2
	212	J. W. Mecom	Univ. of Texas No. 1	1951	1951	1
	213	Humble Oil	State Tract No. 1	—	—	1
	214	C. Y. Kosberg	Agnes Kirsten No. 1	—	—	1
	215	John W. Mecom	Univ. of Texas No. 1	—	1951	2
	216	Shell Petroleum	Maco Stewart & Son No. 2	1937	1937	2
	217	Stewart Petroleum	State Highland Bayou No. 3	1955	—	1
	218	M. Stewart & Company	Stewart Title Guaranty No. 1	1940	1940	1
	219	N. W. Hunter	Stewart Title Guaranty No. 2	1937	—	1
	220	do	Stewart Title Guaranty No. 1	1937	—	1
	221	Stewart Petroleum	State Highland Bayou No. 4	1955	—	1
	222	—	Thomas, et al.	—	—	1
	223	—	M. Stewart	—	—	1

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
U. S. Steel George West Mine, Live Oak Co. DZD 3,200 Feet WDW-123, 124, 130, 140, 141, 174	224	Texas Oil & Gas	Mussman No. 1	1978	1978	2
	225	Penn-Devonian	Lyne No. 1	1935	—	1
	226	Holland Oil	do	—	—	1
	227	Calloway (Holland)	do	—	1936	1
	228	Lysey	Sein No. 1	—	1957	1
	229	O'Neal	—	—	1956	1
	230	Dugger	—	—	1967	2
	231	Calloway	Moczygamba No. 1	—	1936	1
	232	North Central Oil	Harlan-Nelson No. 1	—	1967	2
	233	Caribou	Lyne No. 1-69	—	1973	1
	234	McCarrick	Steinmeyer No. 1	—	1959	2
	235	do	Steinmeyer B-1	—	1959	2
	236	Midwest	Lyne No. 1	—	1962	2
	237	Smith & Stark	Lyne No. 2	—	—	1
	238	Continental Oil	Burns No. 2	—	1960	2
	239	Southland Drilling	Lynn No. 1	1976	1976	2
Vistron Corp. Port Lavaca Plant, Calhoun Co. DZD 6,750 Feet WDW-163, 164, 165	240	Mecom	Welder-Robinson No. 15	—	1952	2 [11.2 lb/gal]
	241	Humble Oil	P. H. Welder No. 29-A	—	—	2, 3
Wastewater, Inc. Guy Facility, Brazoria Co. DZD 6,150 Feet WDW-167	242	Harold Link	J. F. D. Moore W-2	1951	1951	2
	243	Mack Hack Petroleum	J. F. D. Moore W-3	1948	1948	2
	244	F. W. Zelden	Investment & Security W-7	1941	1941	1
	245	Harold Link	J. M. Moore W-10	1950	1950	2

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
Westinghouse Electric Corp. Bruni Mine, Webb Co. DZD 2,900 Feet WDW-170	246	Harvey & Henderson	Benavides No. 1	—	1935	1
	247	Magnolia Petroleum	Volpe-Benavides No. 8	—	1939	2, 3
	248	do	R. Benavides No. 1	—	—	1
	249	do	S. Benavides No. 9	—	1940	2
	250	do	E. Benavides No. 1	—	1934	2
	251	Union Oil	Volpe-Benavides	—	—	1
	252	Magnolia Petroleum	O'Hearn-Benavides	—	—	1
	253	Killam & Anderson	Benavides No. 1	—	1949	2
	254	Schimmel	Volpe No. 1	—	1940	1
	255	National Refining	Benavides No. 1	1925	1925	1
	256	Magnolia Petroleum	S. Jones No. 1	—	1930	2
Witco Chemical Co. Almeda Road Plant, Harris & Fort Bend Co. DZD 5,450 Feet WDW-111, 139	257	W. H. Teel	M. Feld	1950	1950	2
	258	Thompson Drilling	S. Haynie No. 1	1939	1939	1
	259	Sunray DX	C. Arnold No. 1	1966	1966	1
	260	Pure Oil	A. Woods No. 1	1943	1943	2
	261	Maso Oil	W. McCrory No. 1	1956	1956	1
	262	Harrell Drilling	F. Weiser No. 1	1956	1956	2
	263	Cerro del Pasco	M. Feld No. 1	1957	—	1
	264	Jack W. Frazier	N. Waters No. 1	—	—	2
	265	R. A. Johnston	H. Cockburn No. 1	—	—	2
	266	Texoma Petroleum	A. Meyer, et al. No. 1	—	—	2
	267	Oil Production Maintenance	Stanolind No. 1	—	—	2

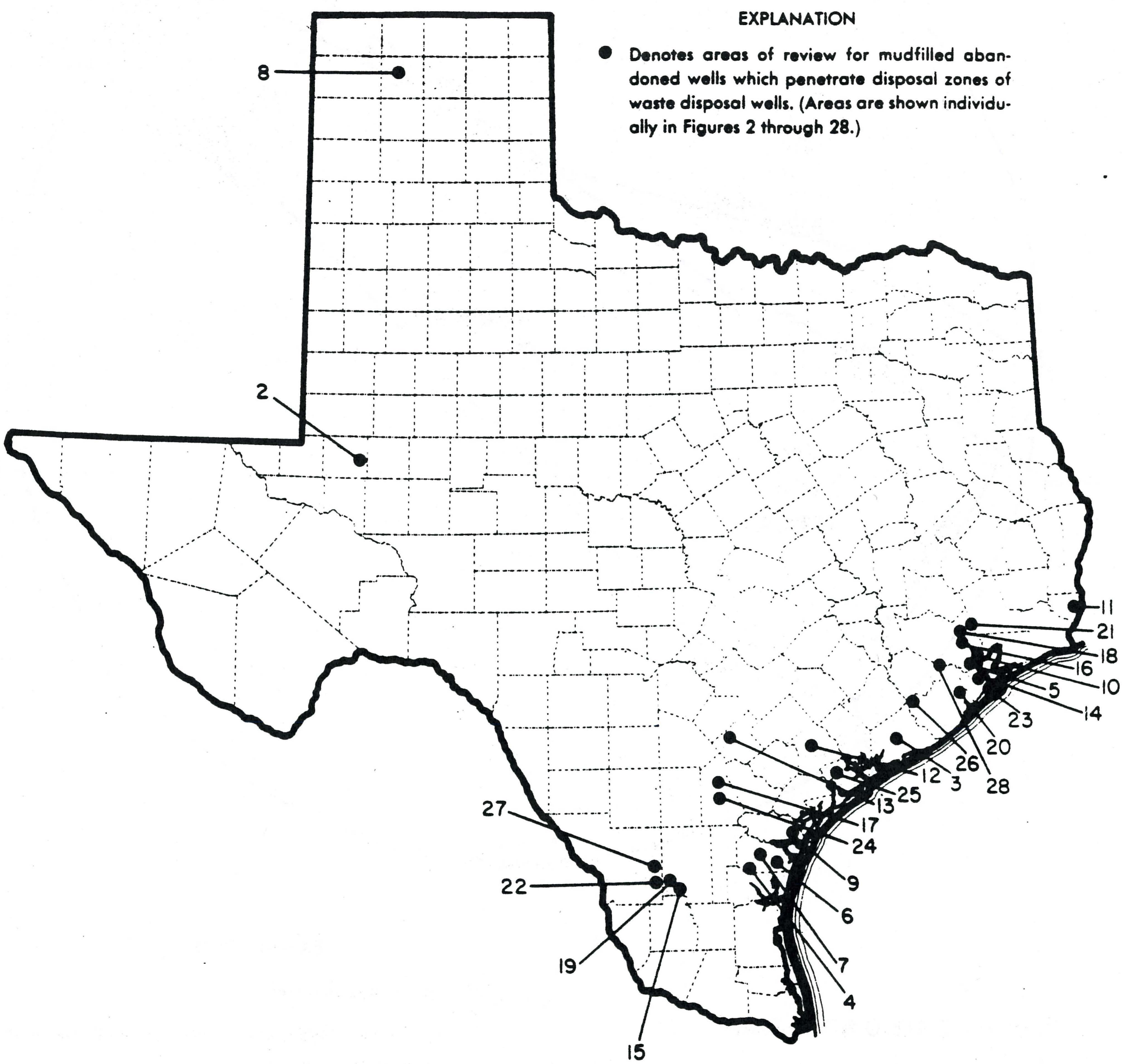


Figure 1--Index map to data in this report

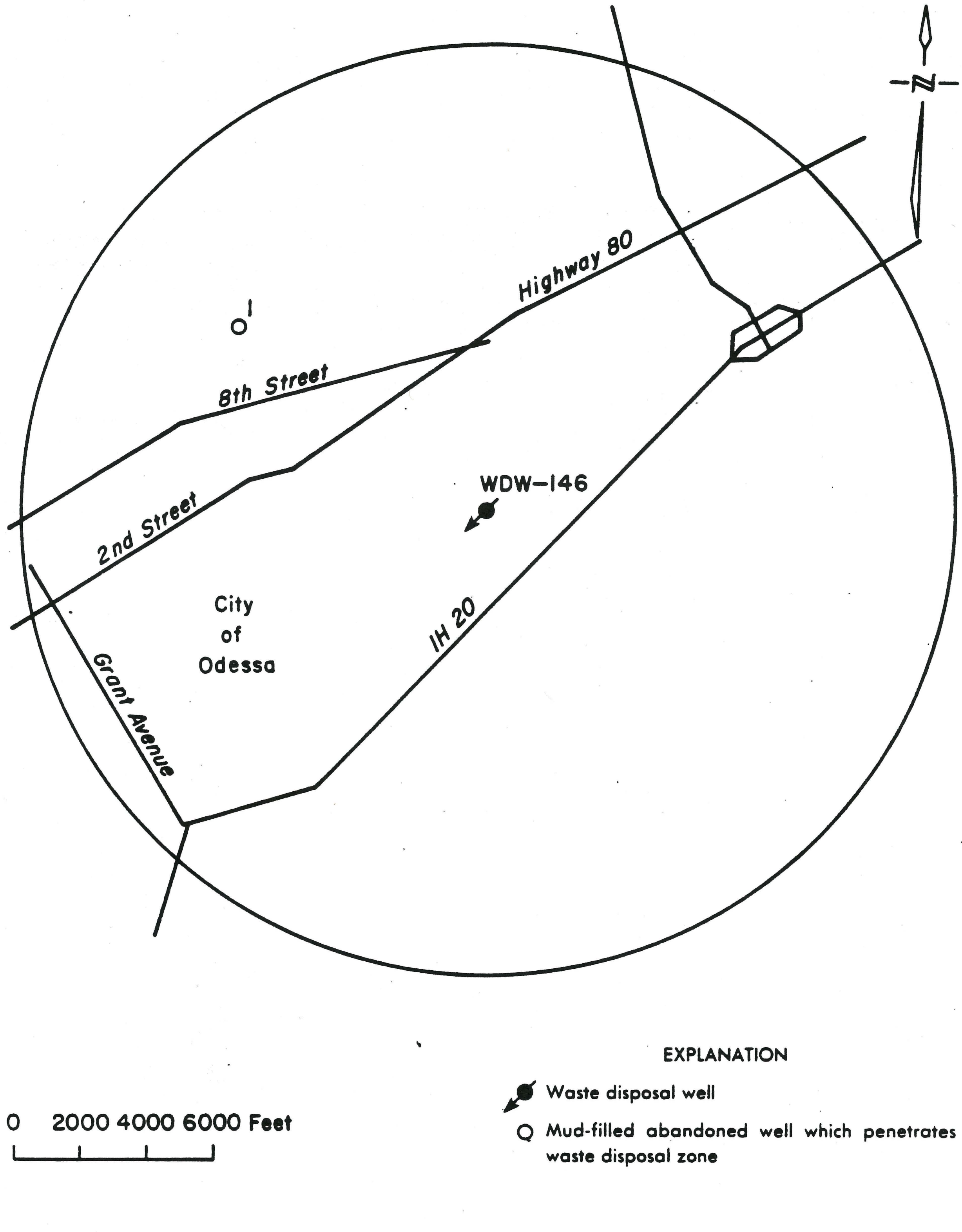


Figure 2--Area of review for CECOS International waste disposal well, Odessa Facility, Ector County

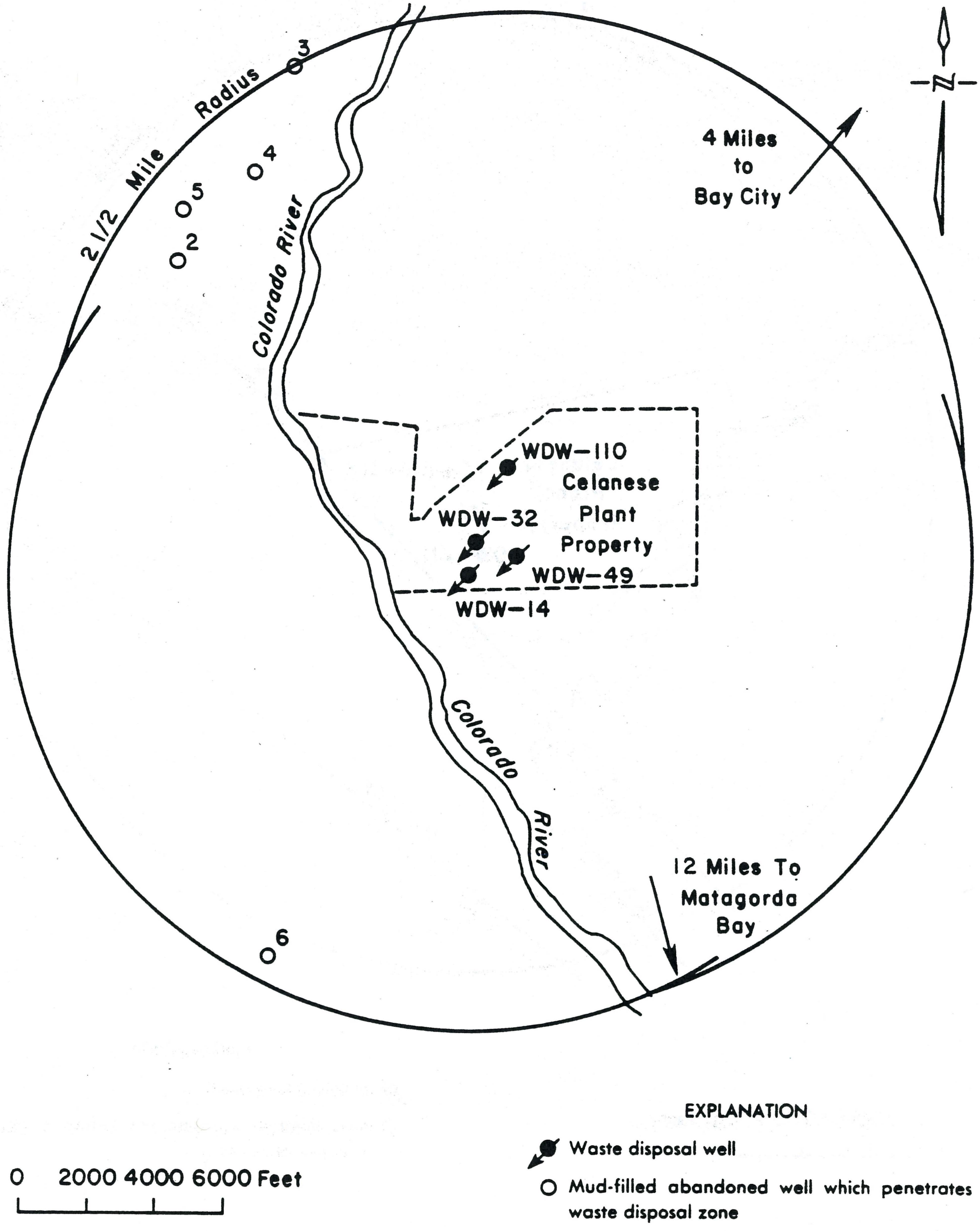


Figure 3--Area of review for Celanese Chemical Co. waste disposal wells, Bay City Plant, Matagorda County

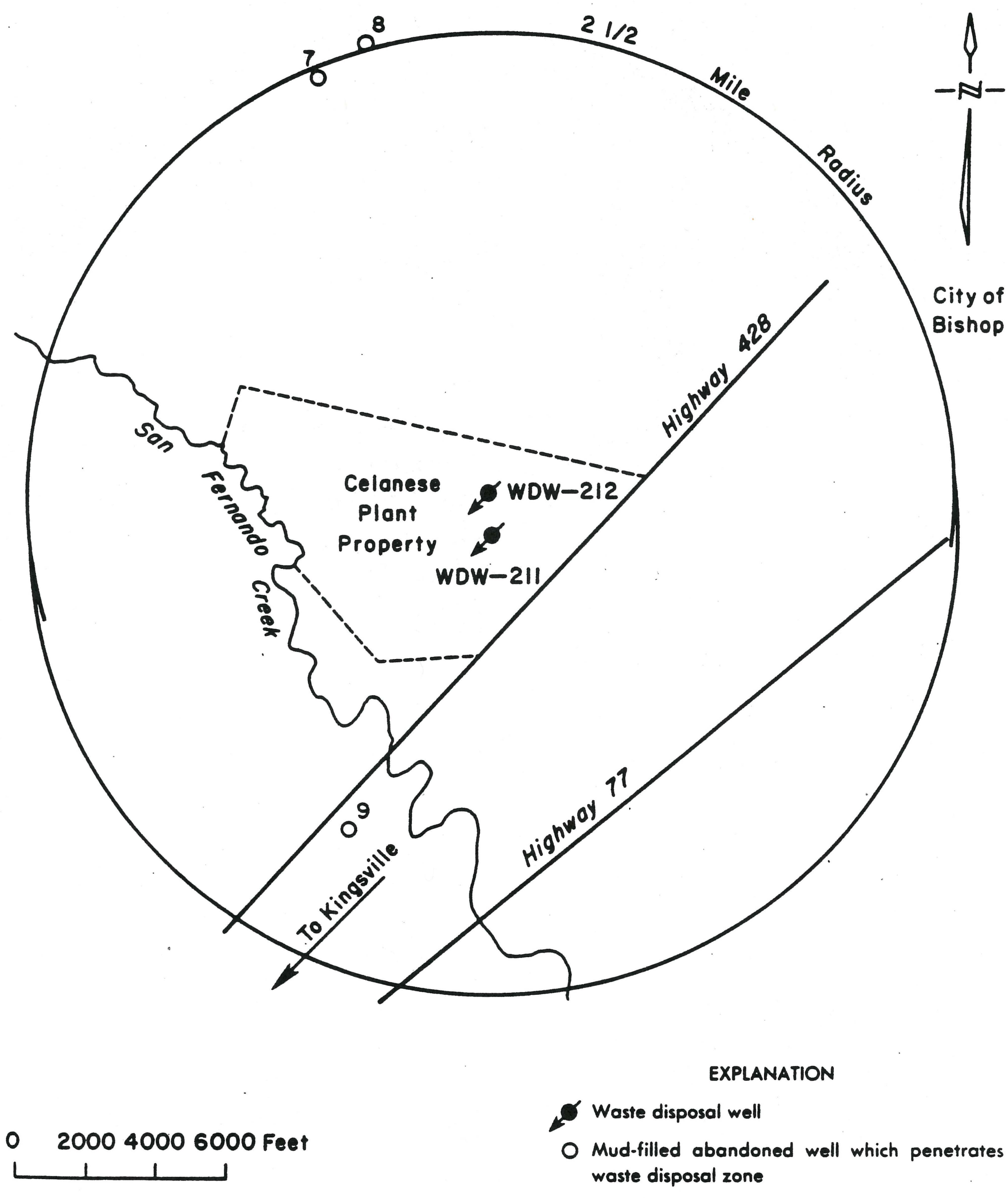


Figure 4--Area of review for Celanese Chemical Co. waste disposal wells, Bishop Plant, Nueces County

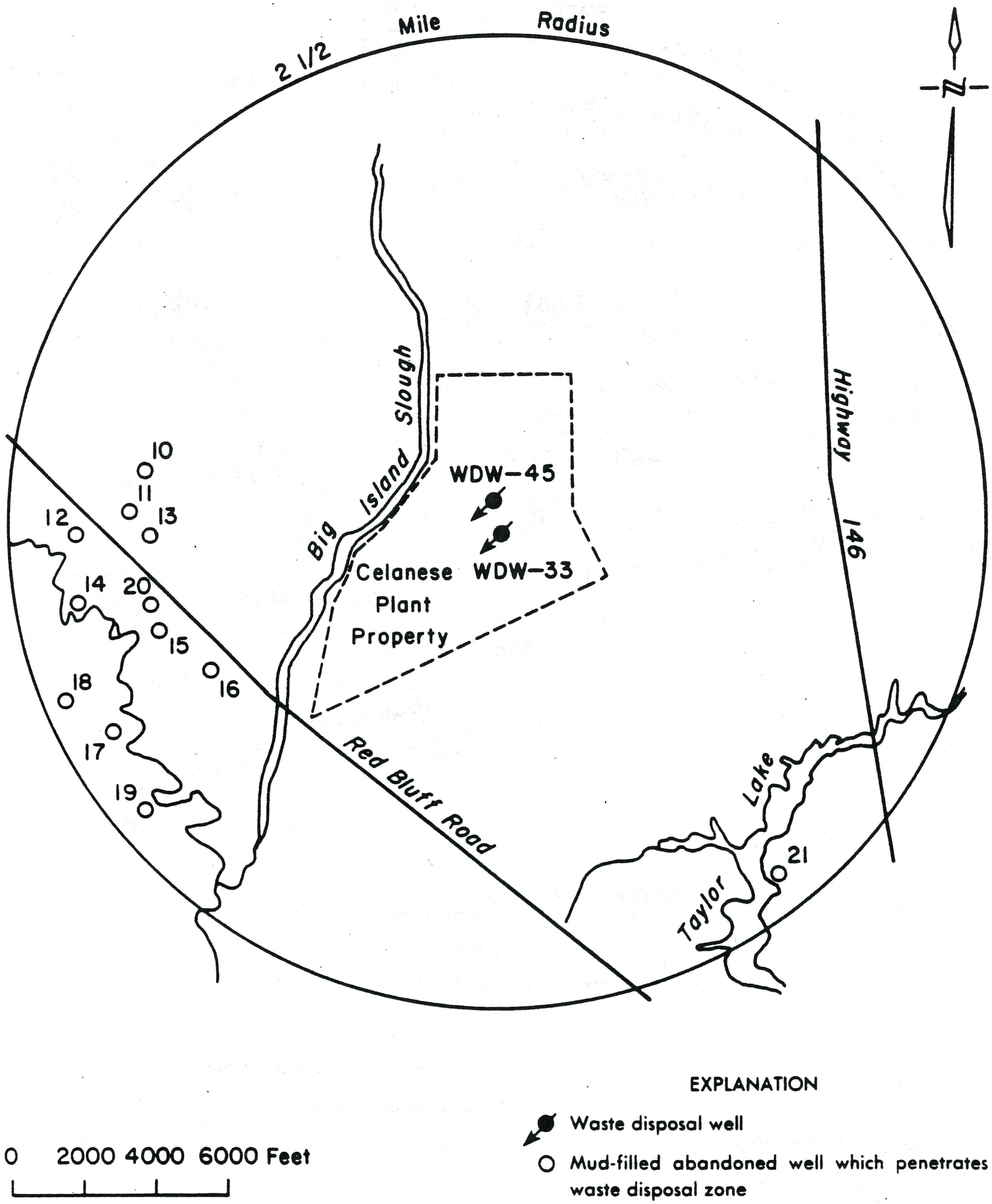


Figure 5--Area of review for Celanese Chemical Co. waste disposal wells, Clear Lake Plant, Harris County

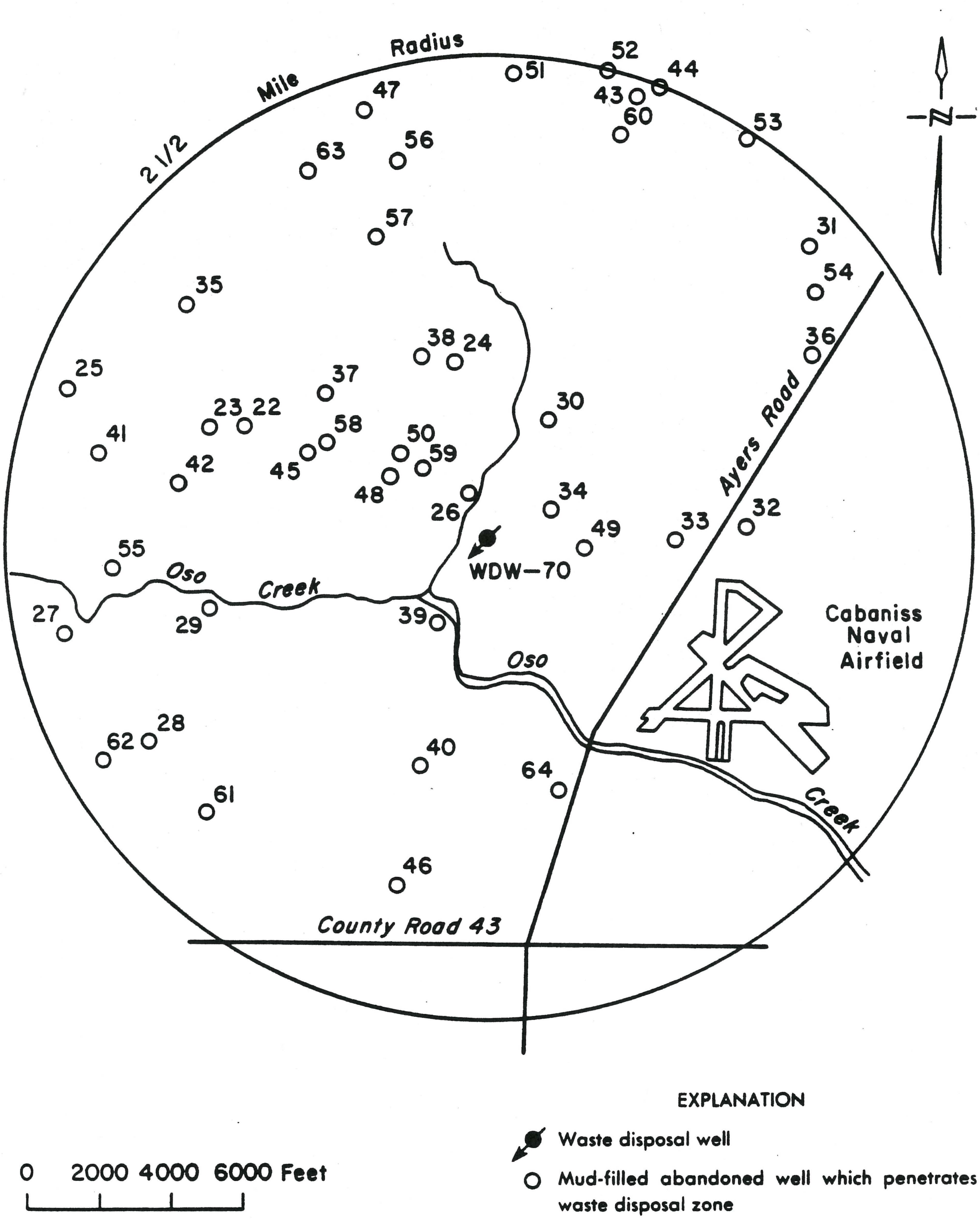


Figure 6--Area of review for Chemical Waste Management waste disposal well, Corpus Christi Plant, Nueces County

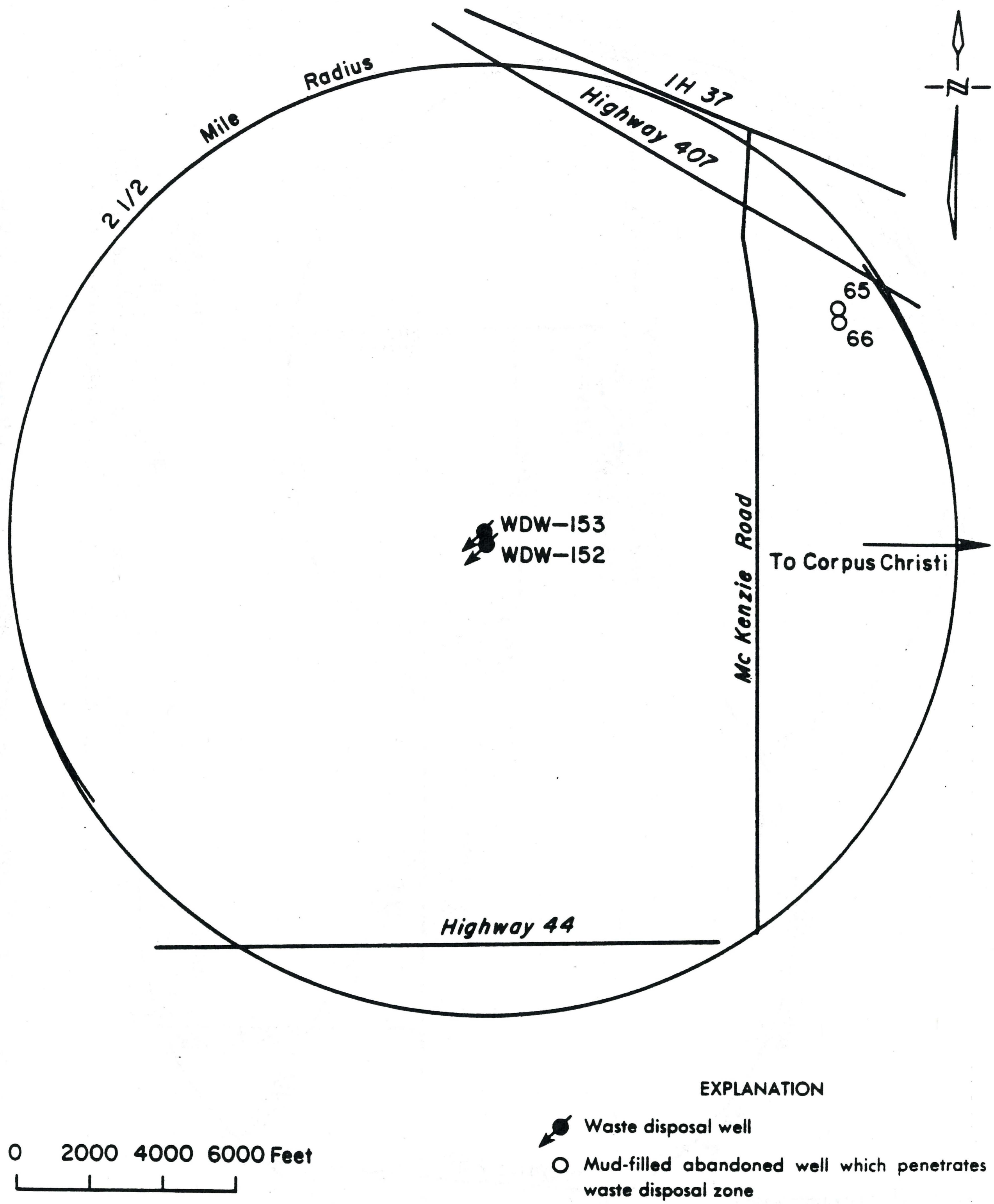


Figure 7--Area of review for Corpus Christi Petrochemical Co. waste disposal wells, Robstown Plant, Nueces County

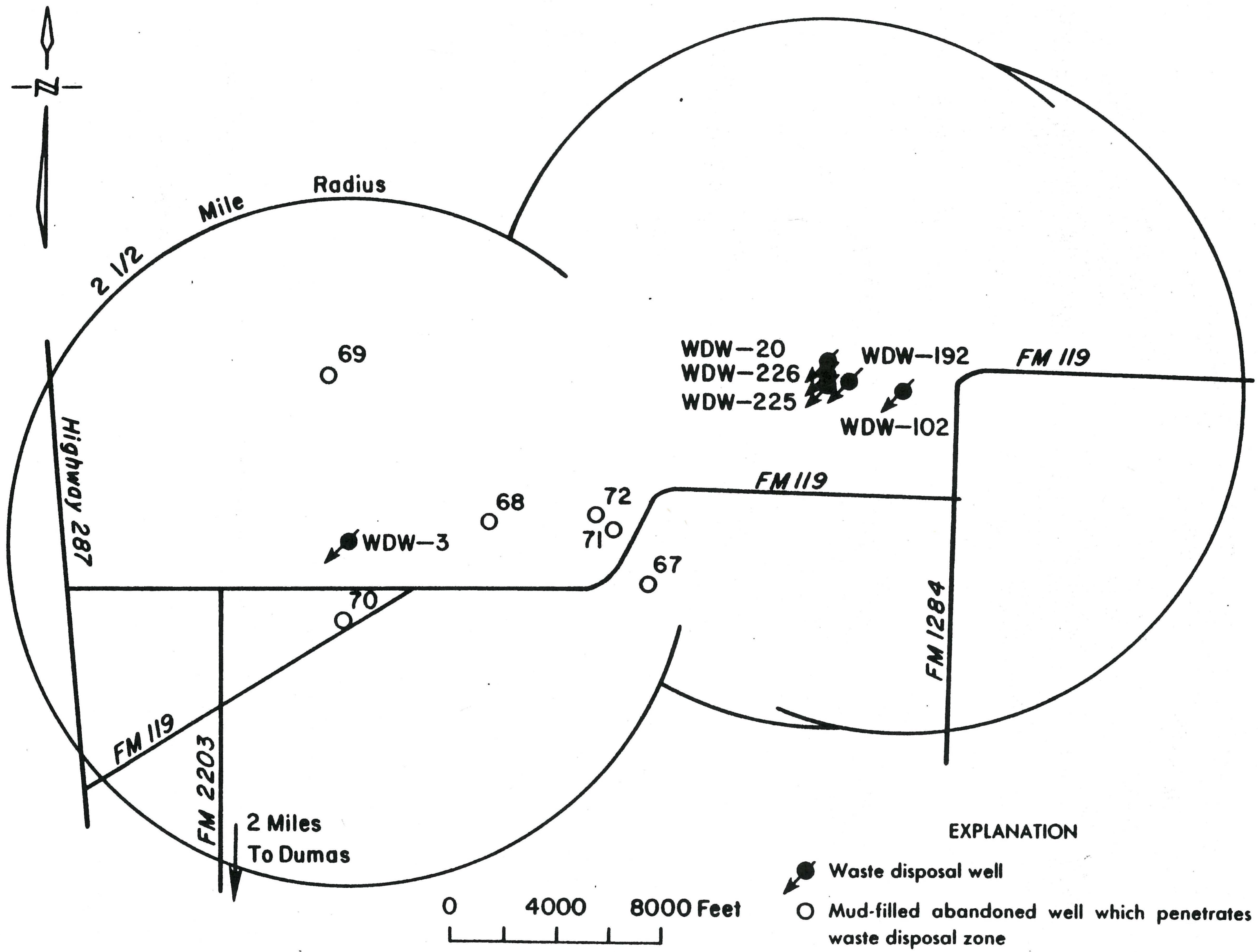


Figure 8--Area of review for waste disposal wells near Dumas, Moore County: Diamond Shamrock Corp. and Potash Co. of America

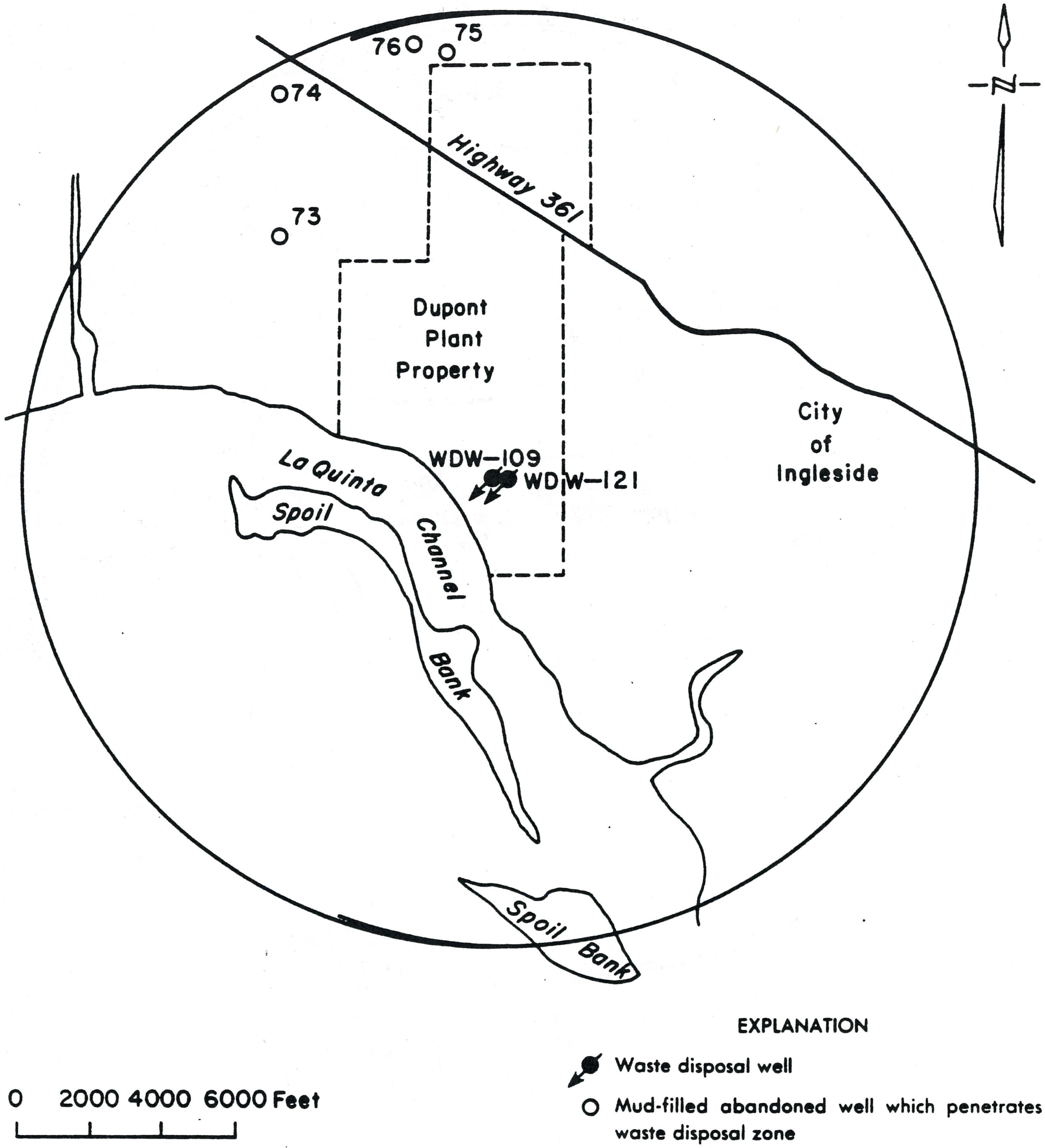
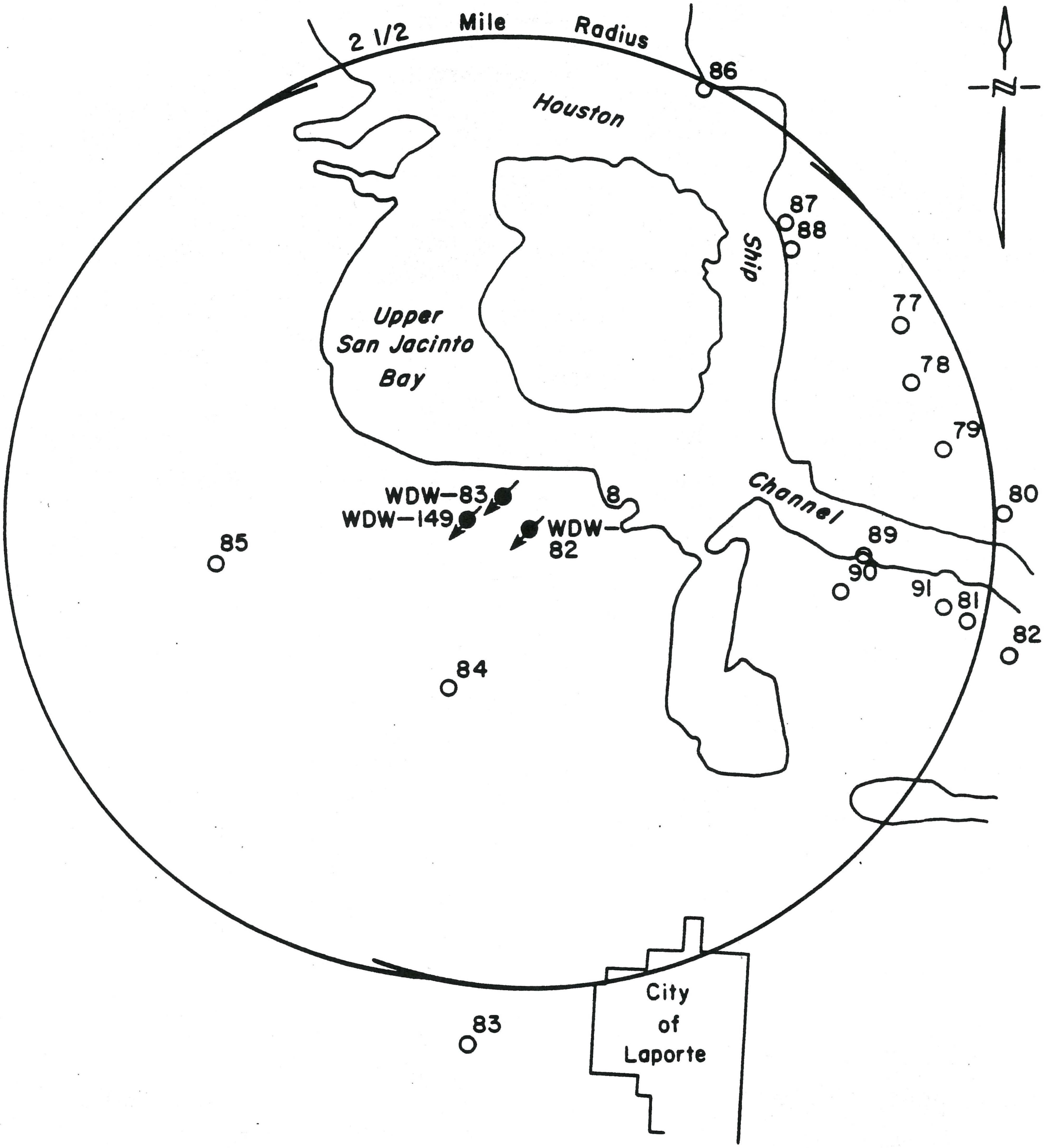
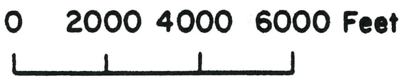


Figure 9--Area of review for E. I. Dupont de Nemours & Co. waste disposal wells, Corpus Christi Plant, San Patricio County





EXPLANATION

Waste disposal well

O Mud-filled abandoned well which penetrates waste disposal zone

Figure 10--Area of review for E. I. Dupont de Nemours & Co. waste disposal wells, La Porte Plant, Harris County

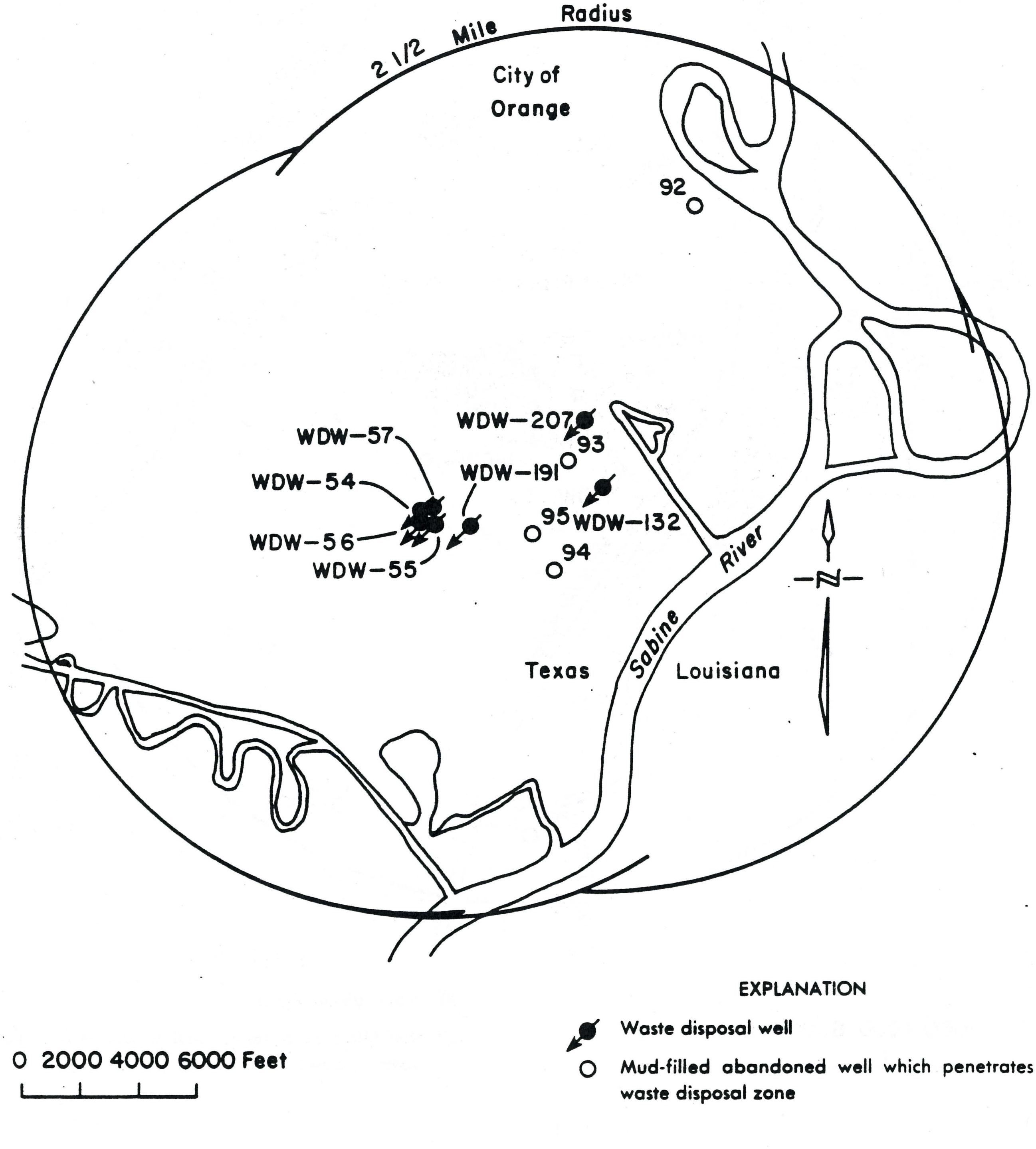


Figure 11--Area of review for E. I. Dupont de Nemours & Co. waste disposal wells, Sabine River Works, Orange County

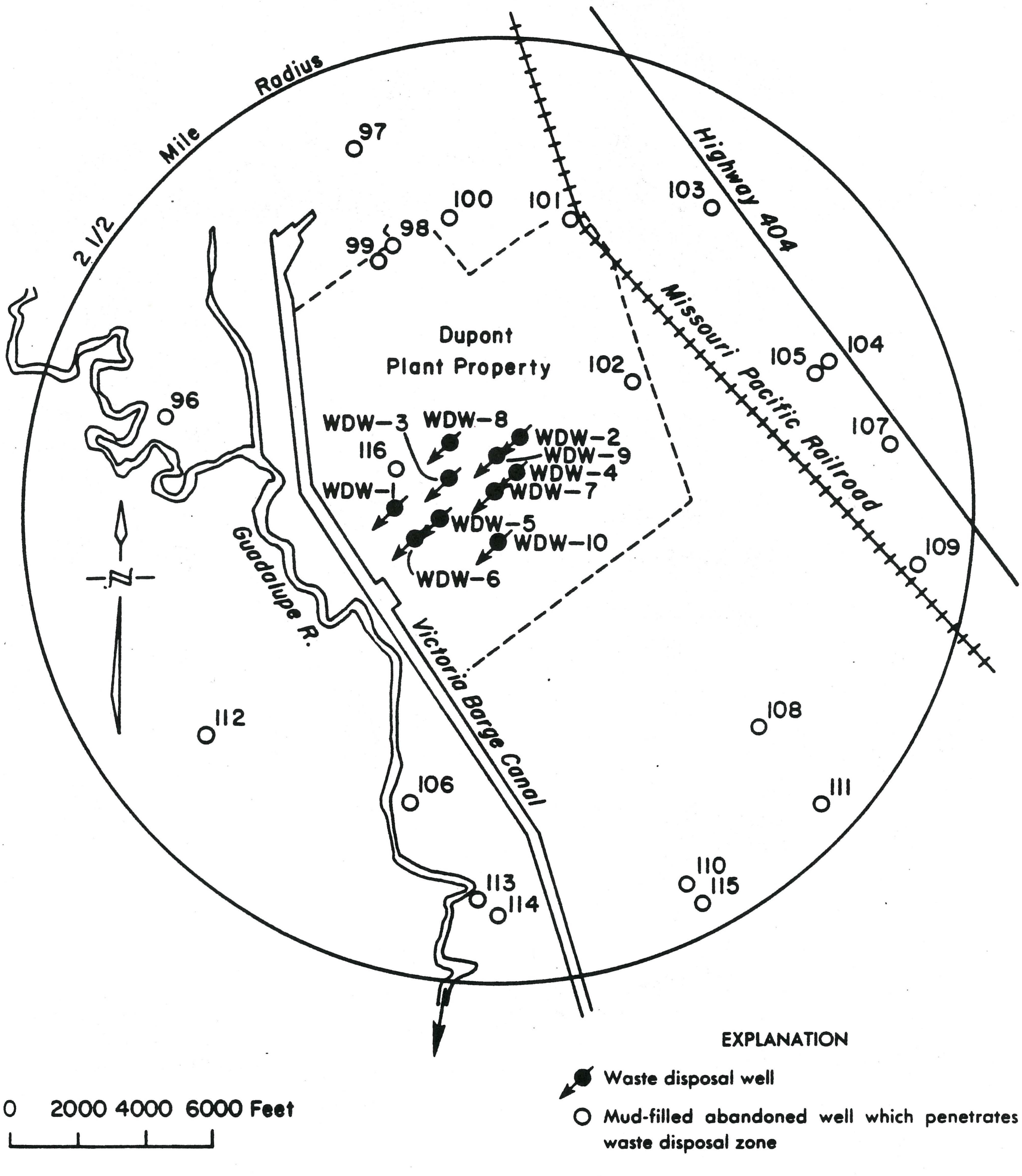


Figure 12--Area of review for E. I. Dupont de Nemours & Co. waste disposal wells, Victoria Plant, Victoria County

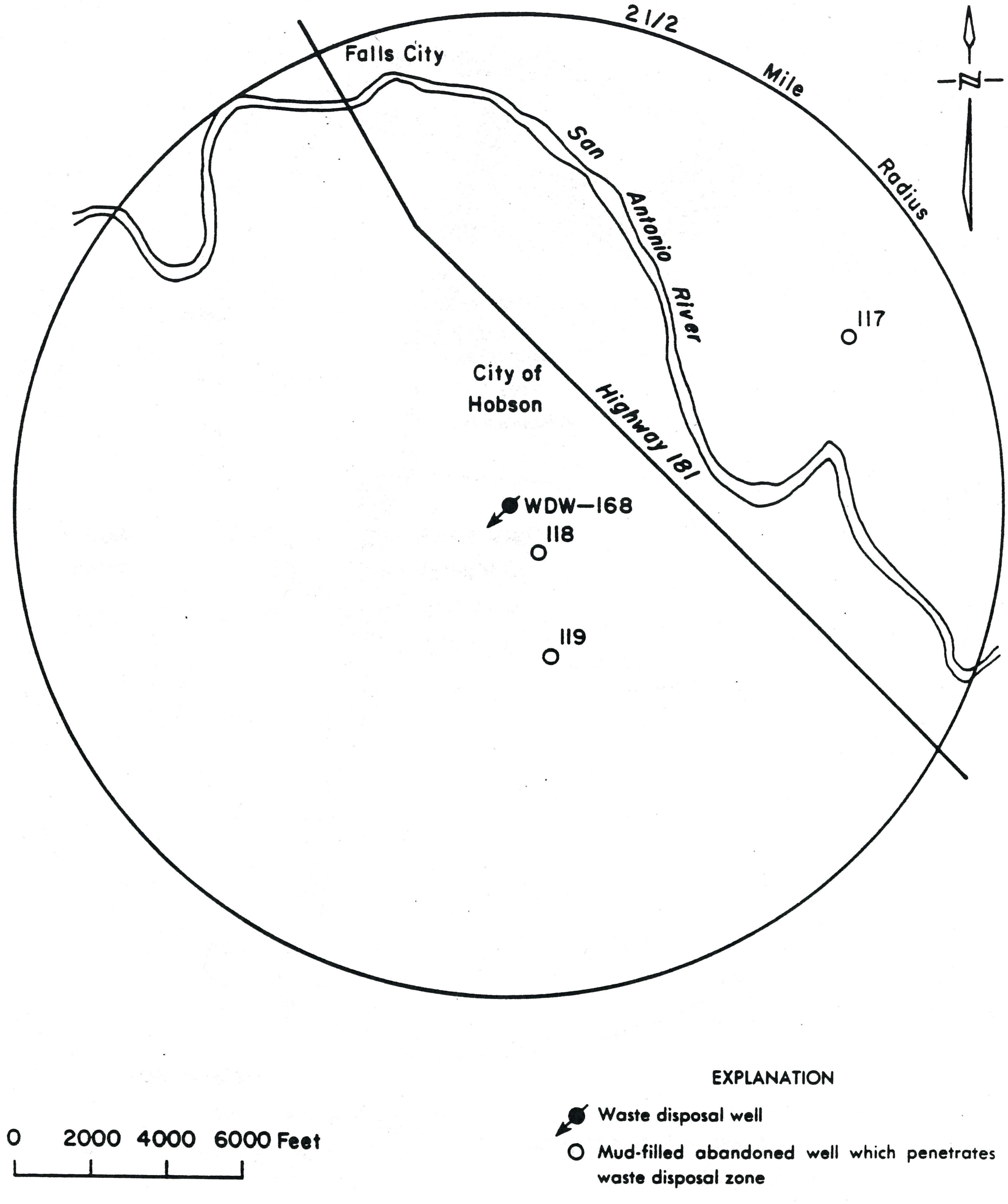


Figure 13--Area of review for Everest Minerals Corp. waste disposal well, Hobson Mine, Karnes County

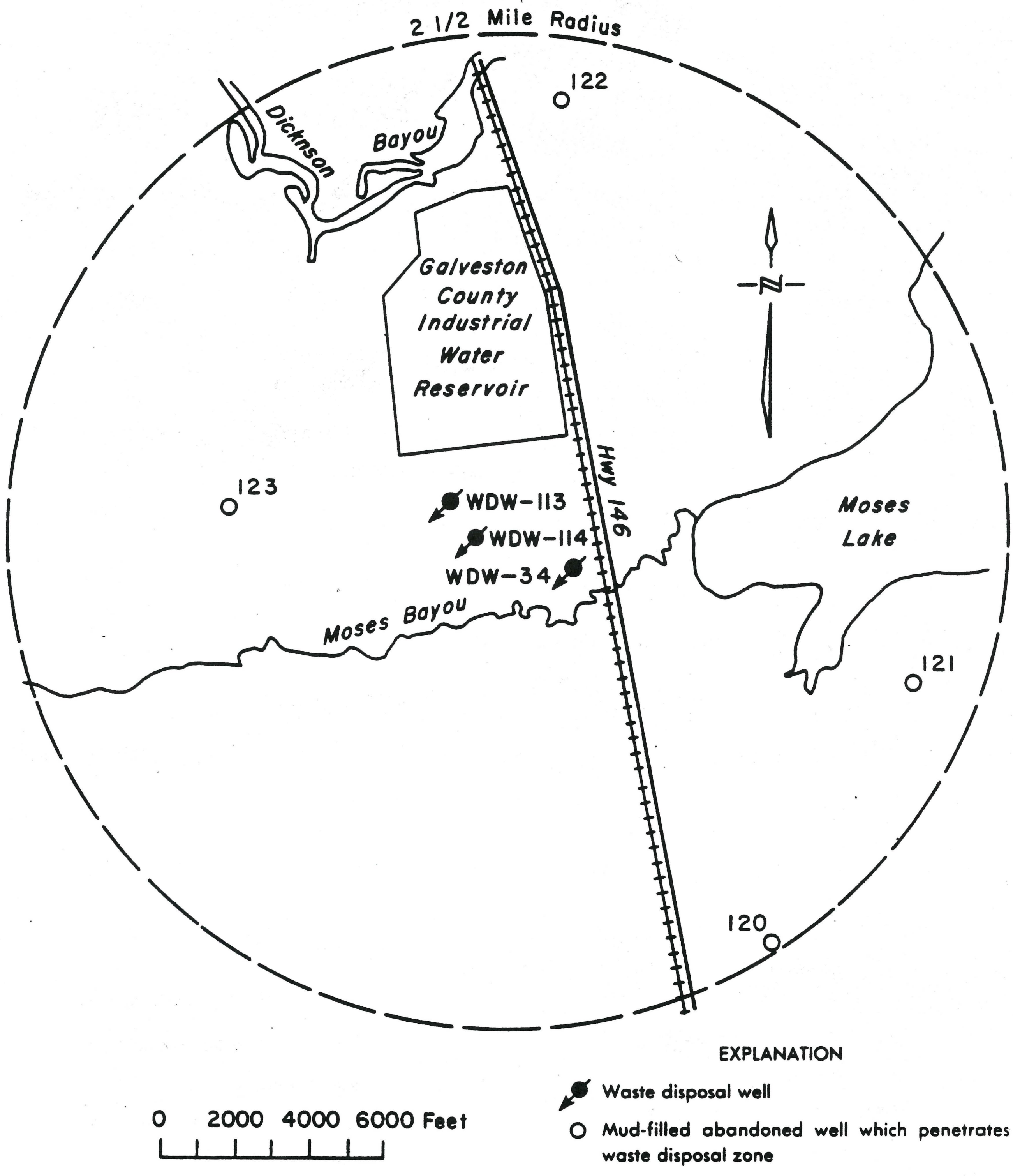


Figure 14--Area of review for GAF Corp. waste disposal wells, Texas City Plant, Galveston County

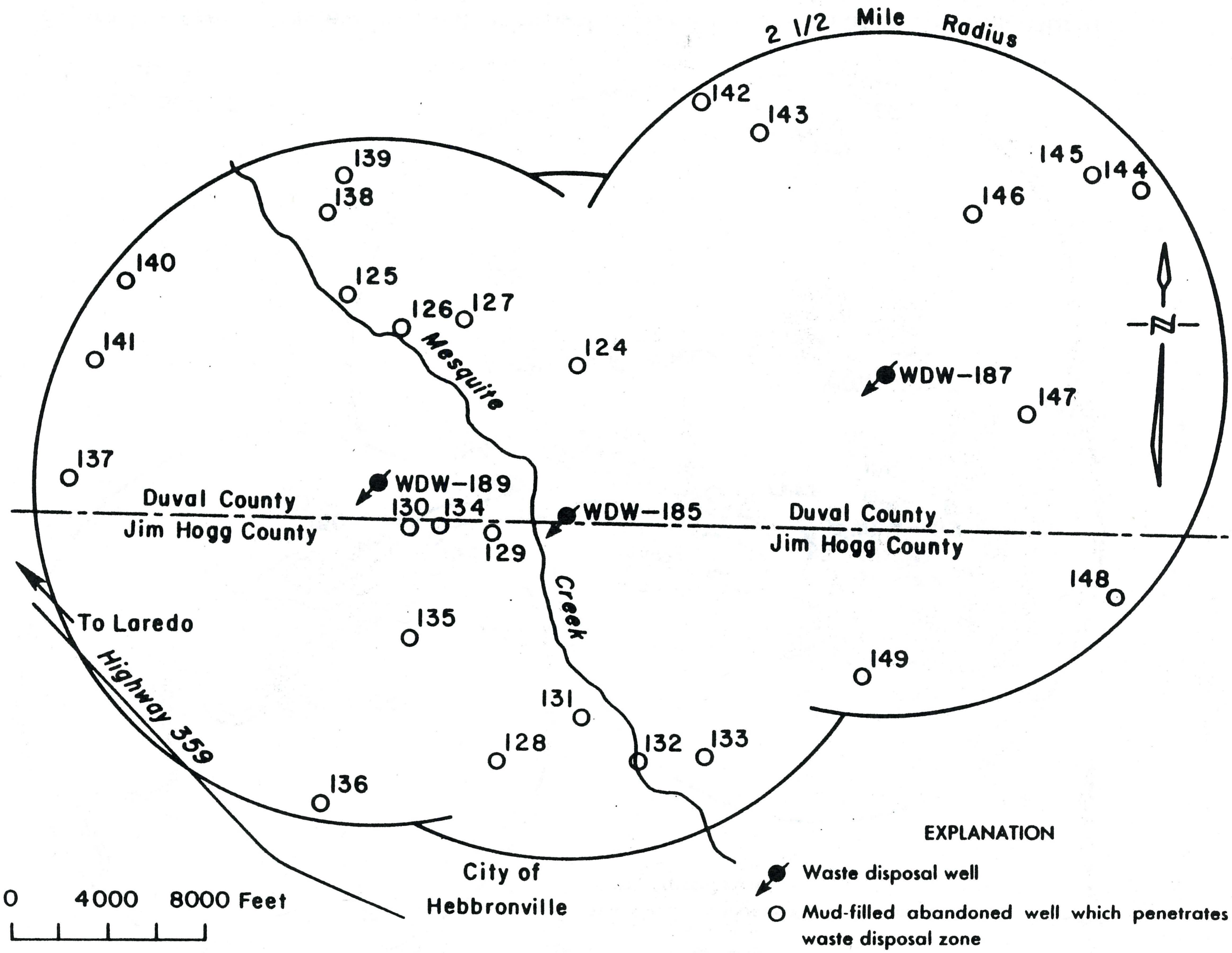


Figure 15--Area of review for waste disposal wells near Hebbronville, Duval and Jim Hogg Counties: Caithness Mining Corp., Conoco, Inc., and Everest Minerals Corp.

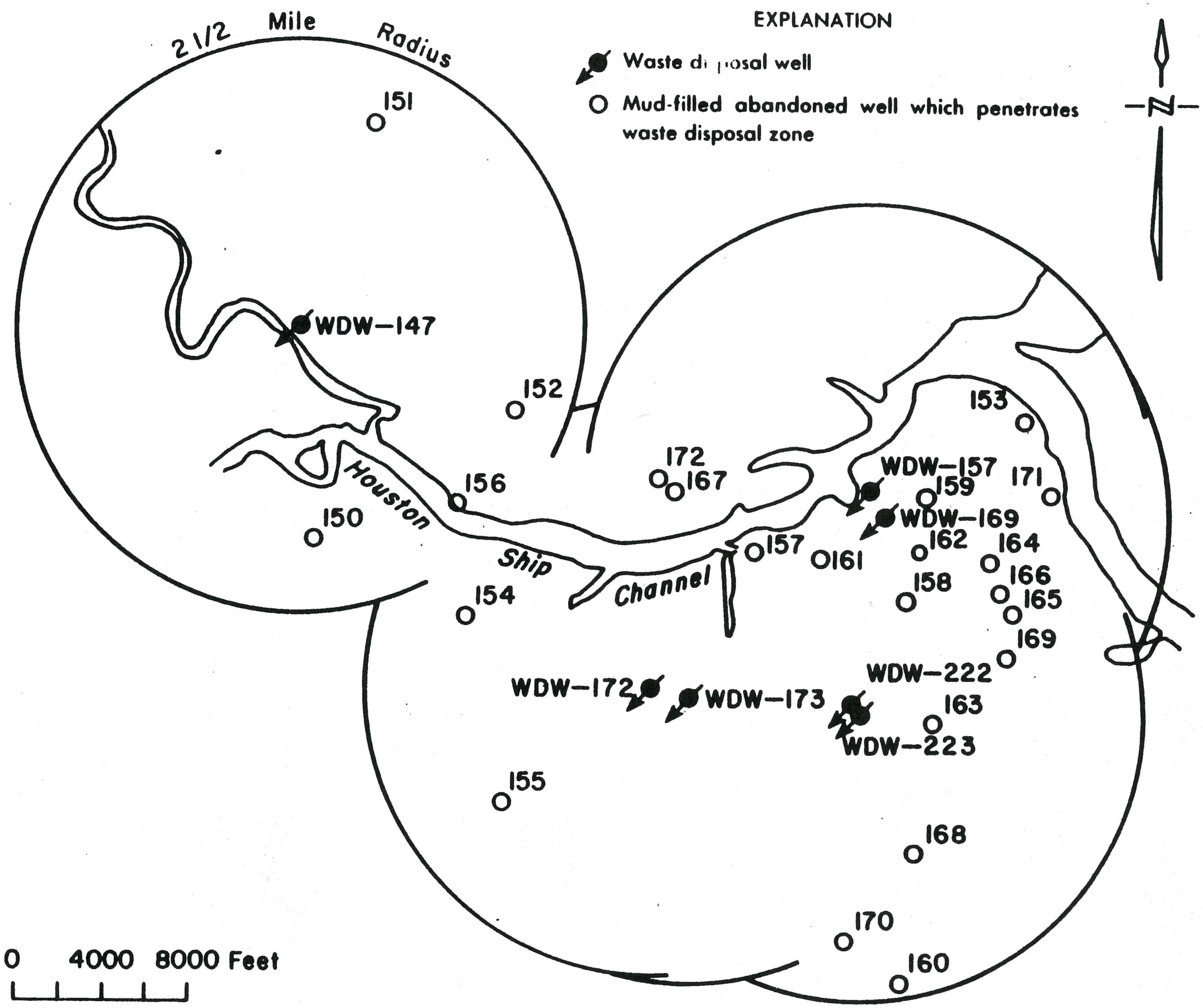


Figure 16--Area of review for waste disposal wells near Houston Ship Channel, Harris County: Empak, Inc., Disposal Systems, W. R. Grace & Co., Merichem Co., and Shell Chemical Co.

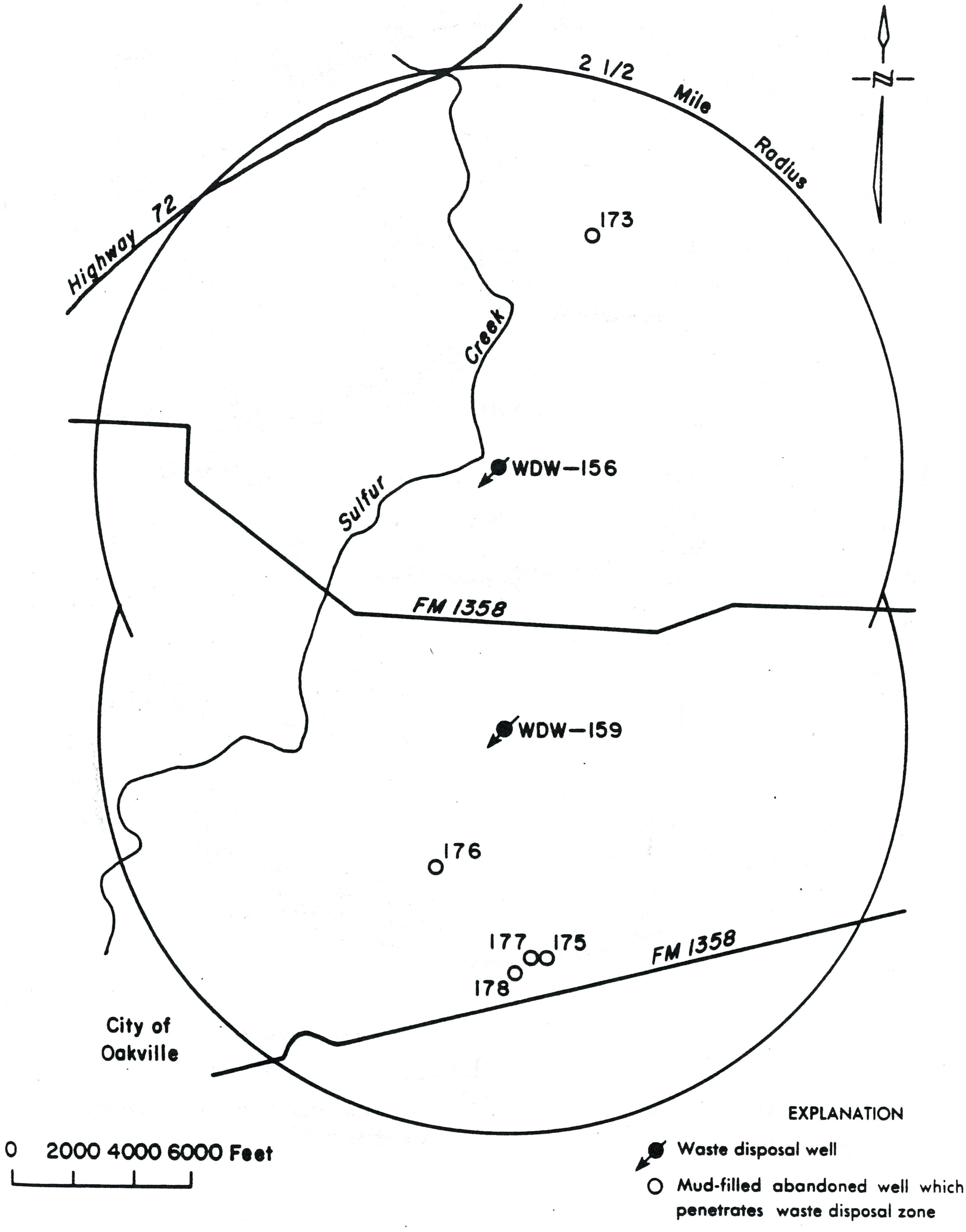


Figure 17--Area of review for IEC Corp. waste disposal wells, Lamprecht and Zamzow Mines, Live Oak County

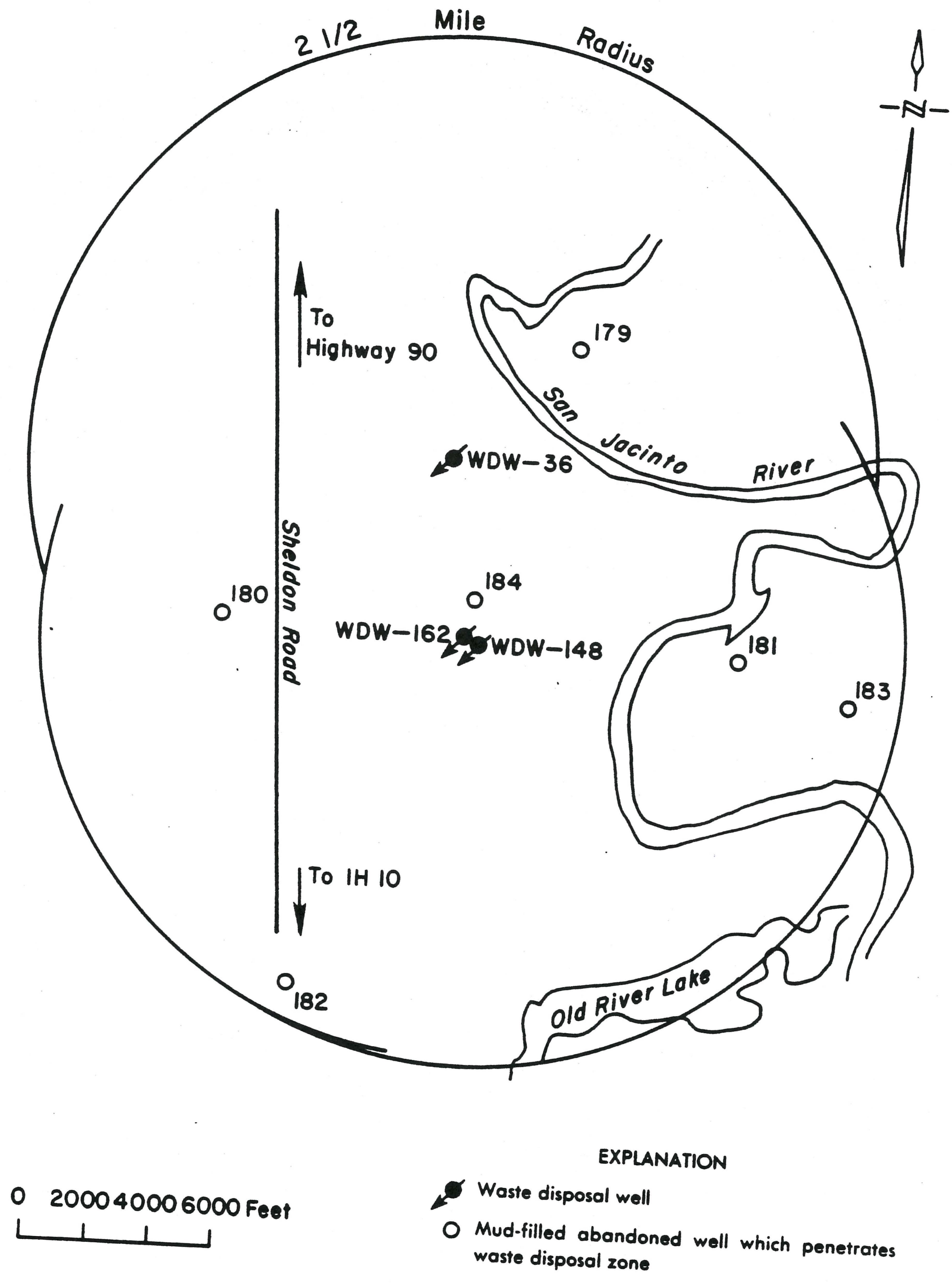


Figure 18--Area of review for Lyondell Petrochemical Co. waste disposal wells, Channelview Plant, Harris County

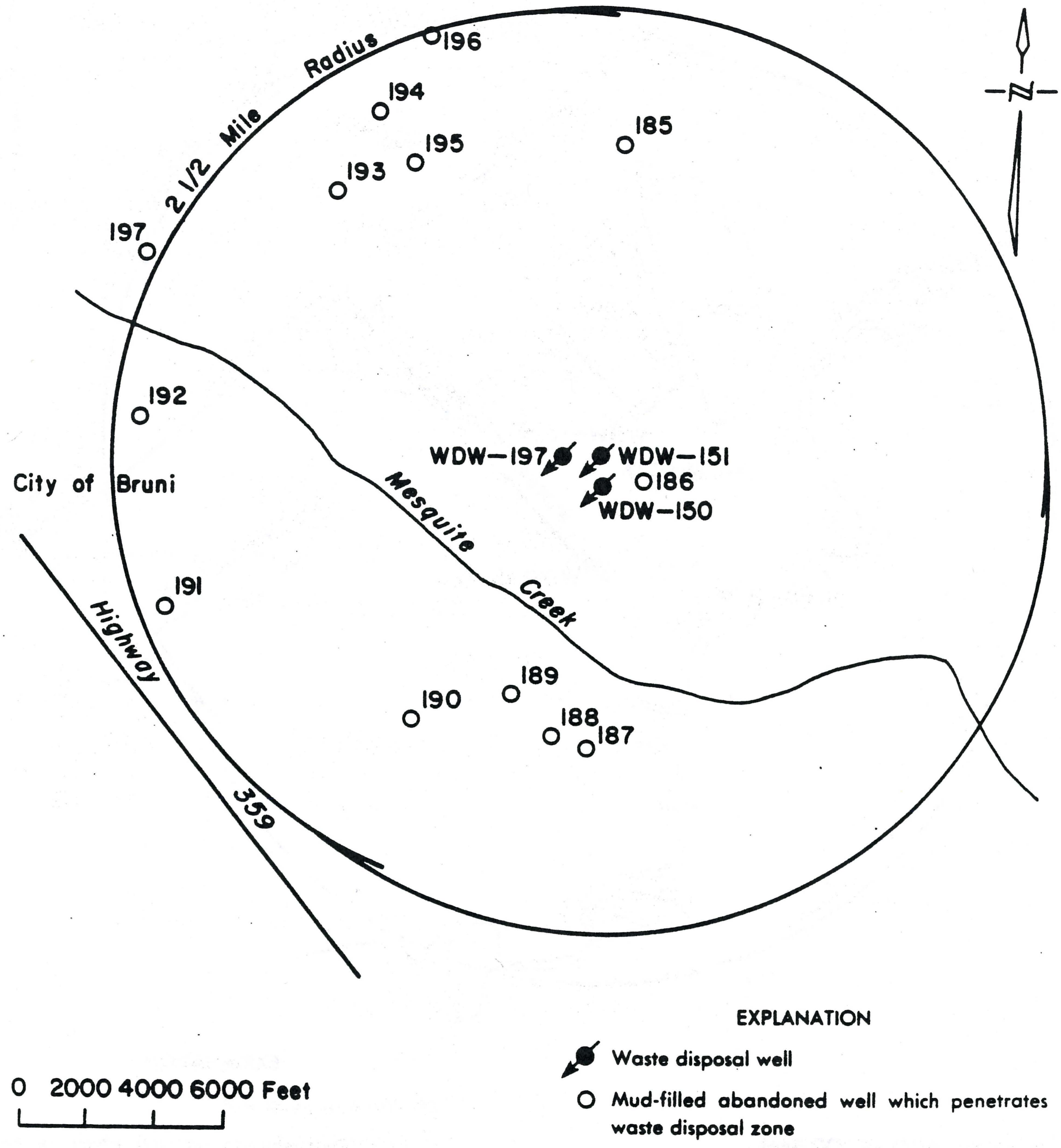


Figure 19--Area of review for Mobil Oil Corp. waste disposal wells, Holiday/El Mesquite Mine, Webb County

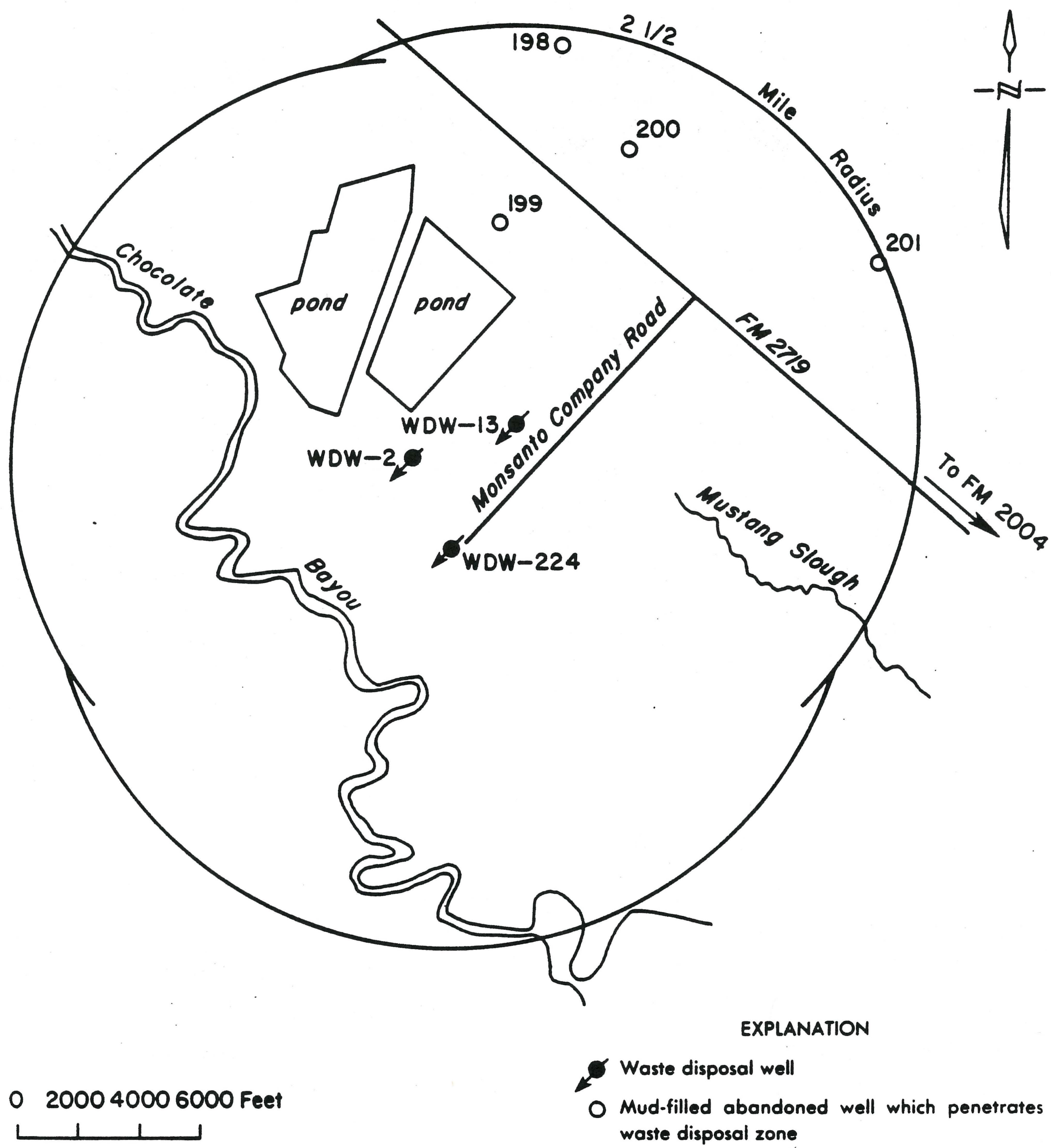


Figure 20--Area of review for Monsanto Chemical Co. waste disposal wells, Chocolate Bayou Plant, Brazoria County

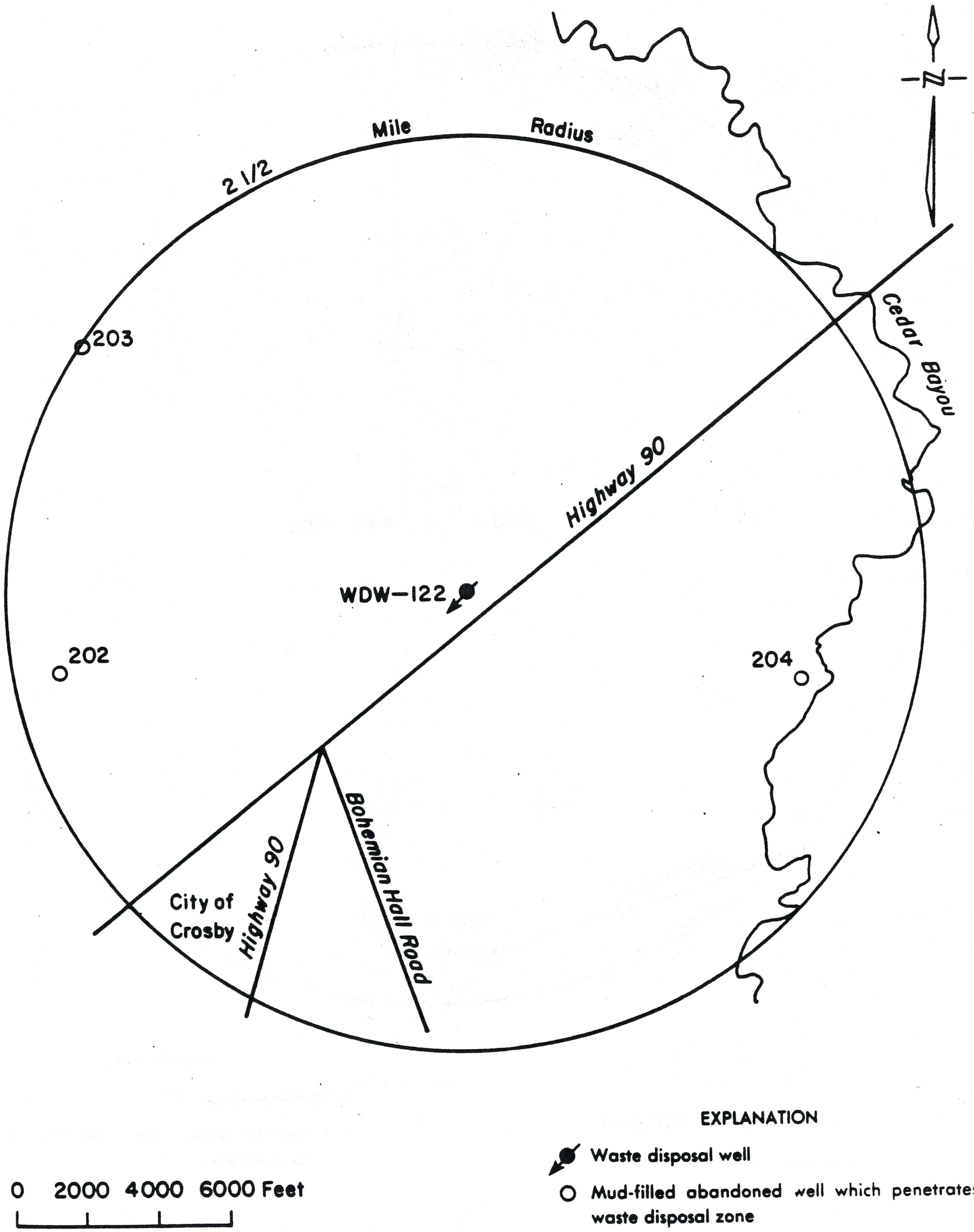


Figure 21--Area of review for Penwalt Corp. waste disposal well, Crosby Plant, Harris County

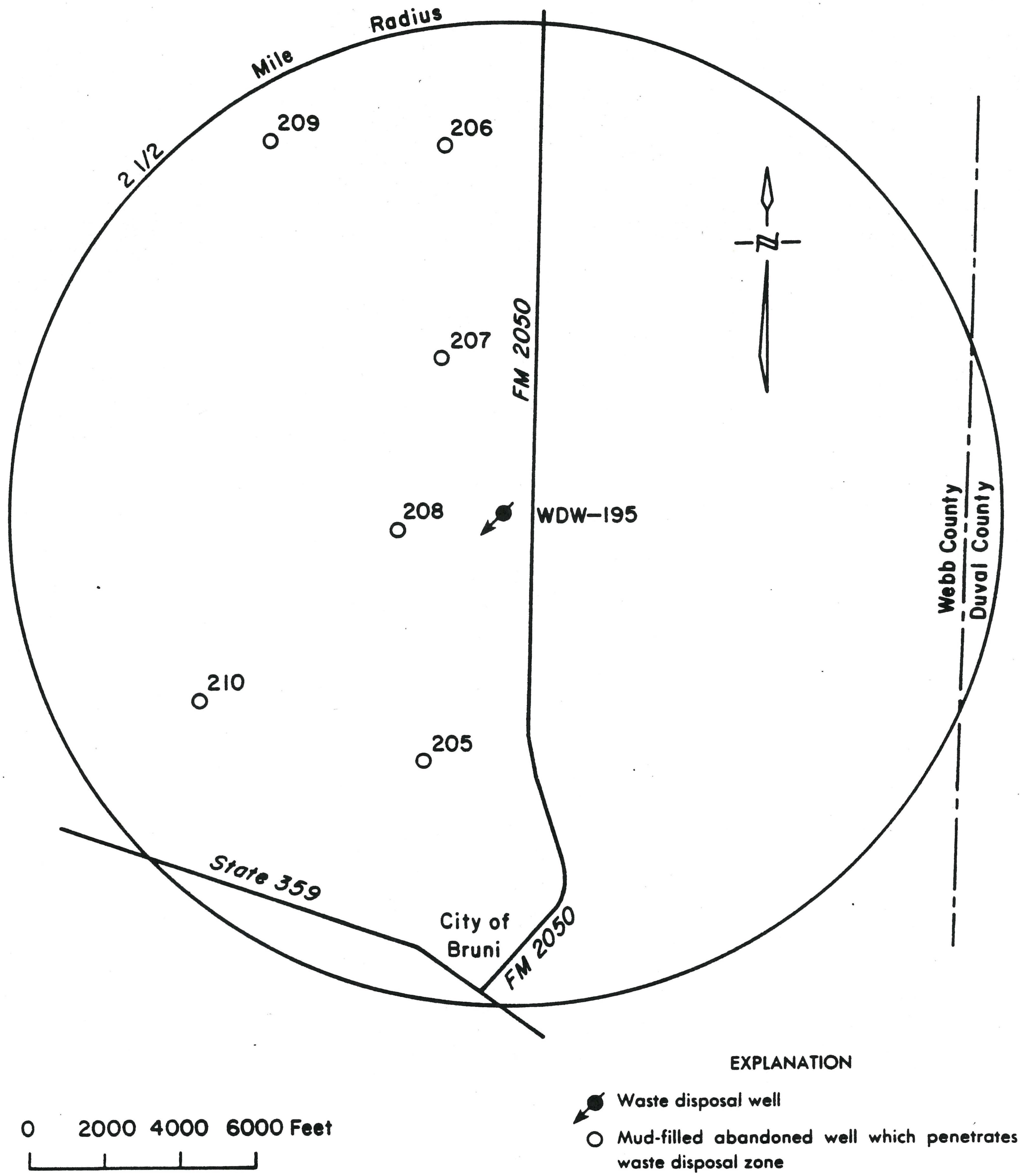


Figure 22--Area of Review for Tenneco Uranium, Inc. waste disposal well, West Cole Mine, Duval and Webb Counties

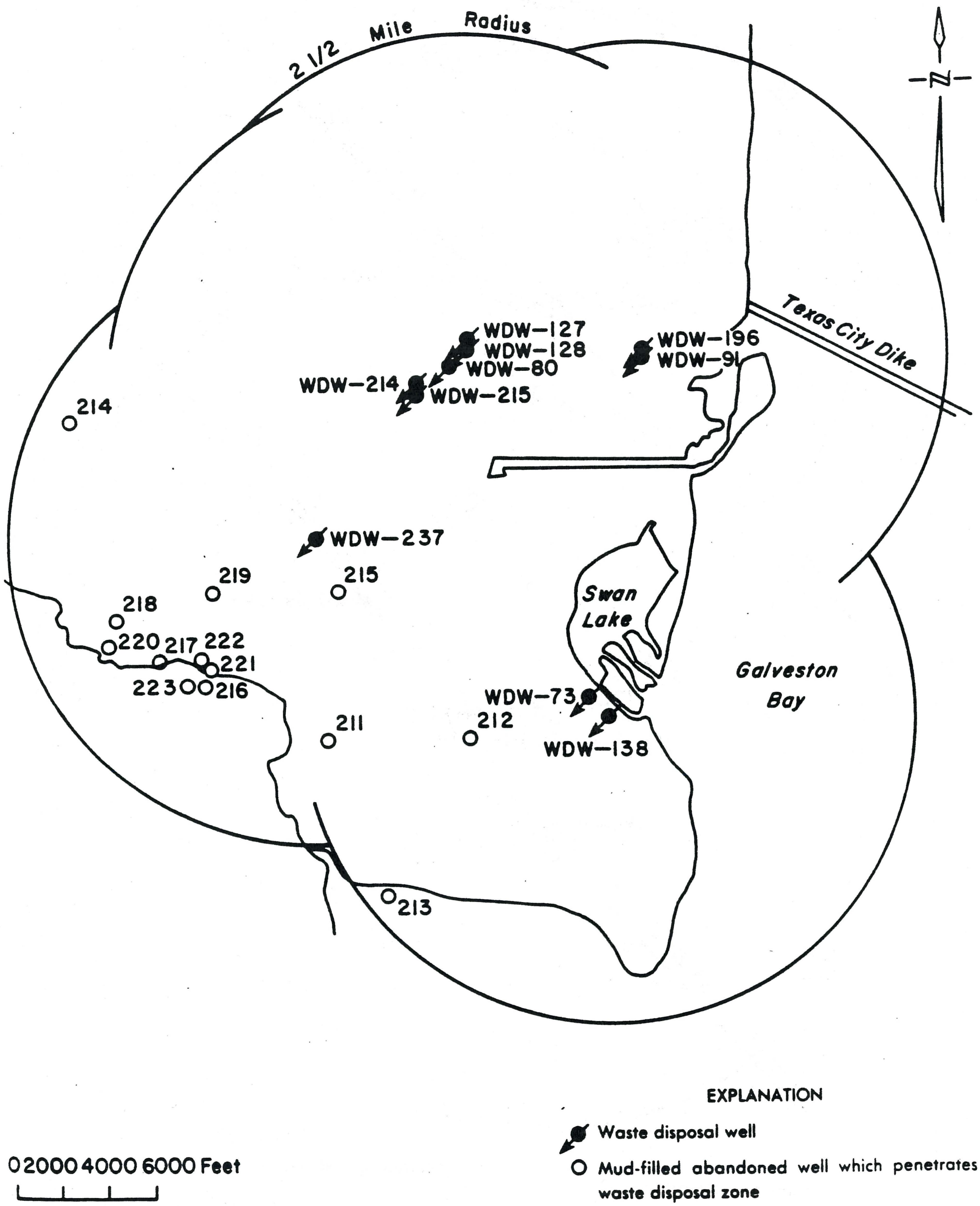


Figure 23--Area of review for waste disposal wells near Texas City, Galveston County: Amoco Oil Co., Malone Service Co., Monsanto Chemical Co., and Textin, Inc.

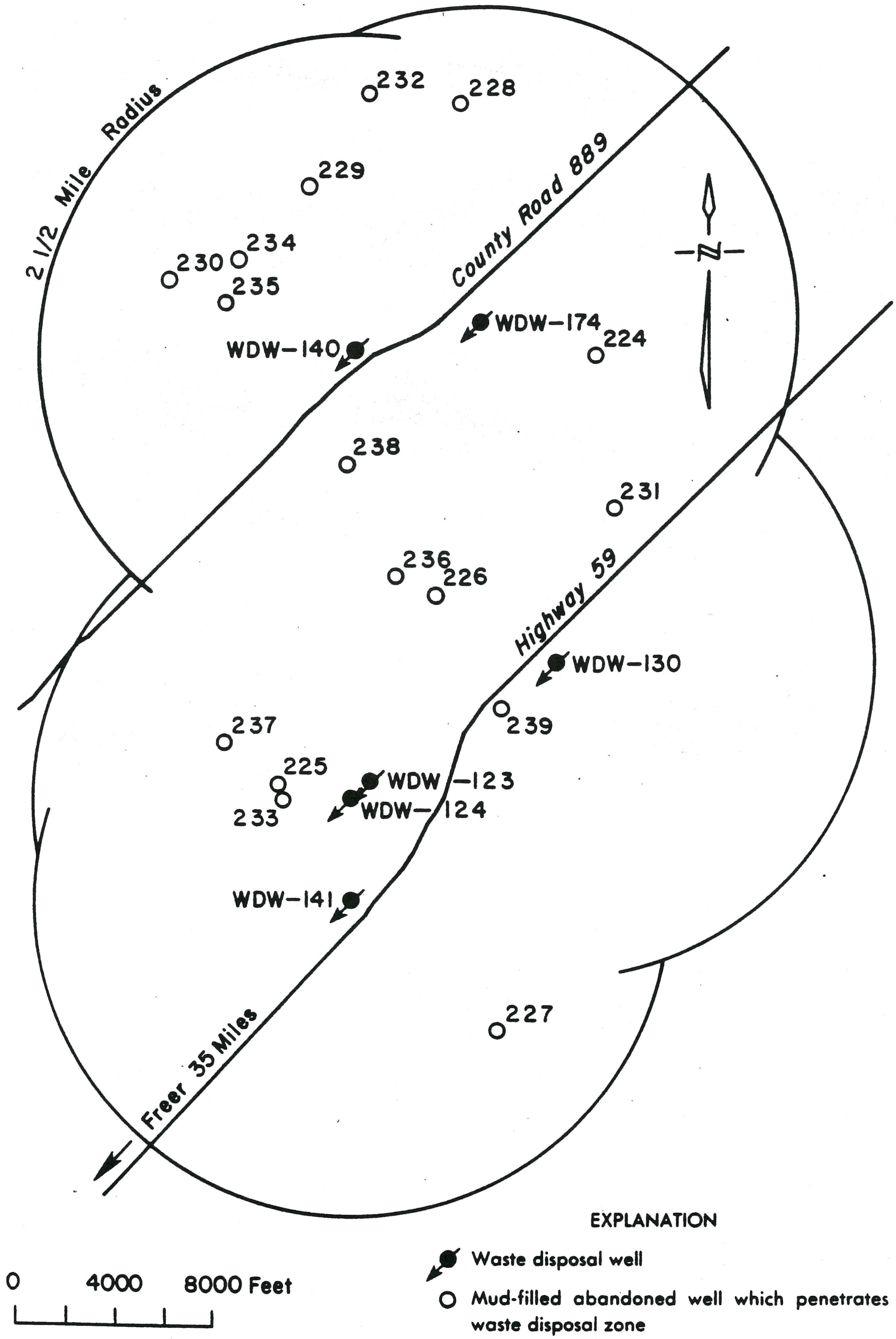


Figure 24--Area of review for U. S. Steel Corp. waste disposal wells, George West Sites, Live Oak County

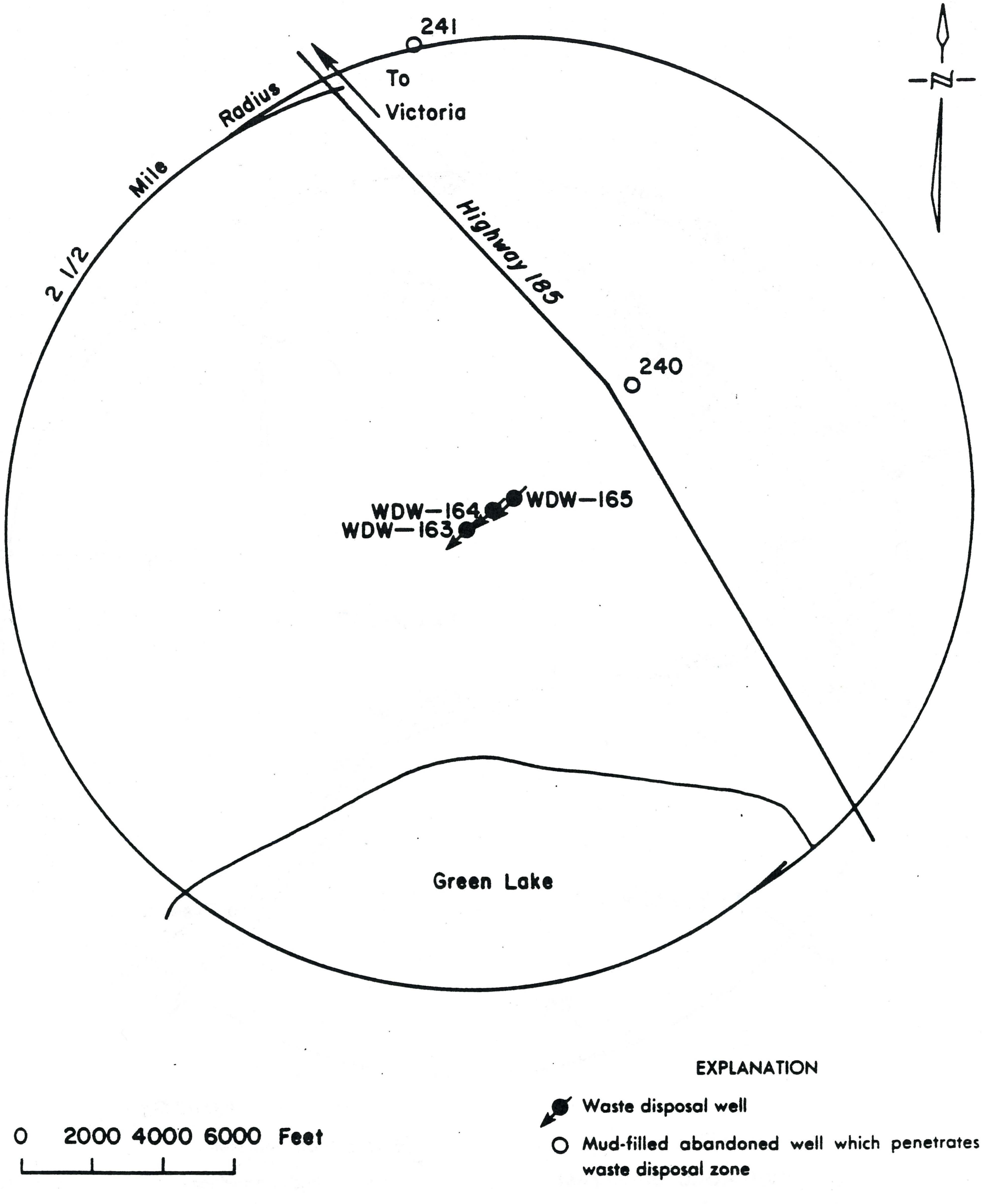


Figure 25--Area of review for Vistron Corp. waste disposal wells, Port Lavaca Plant, Calhoun County

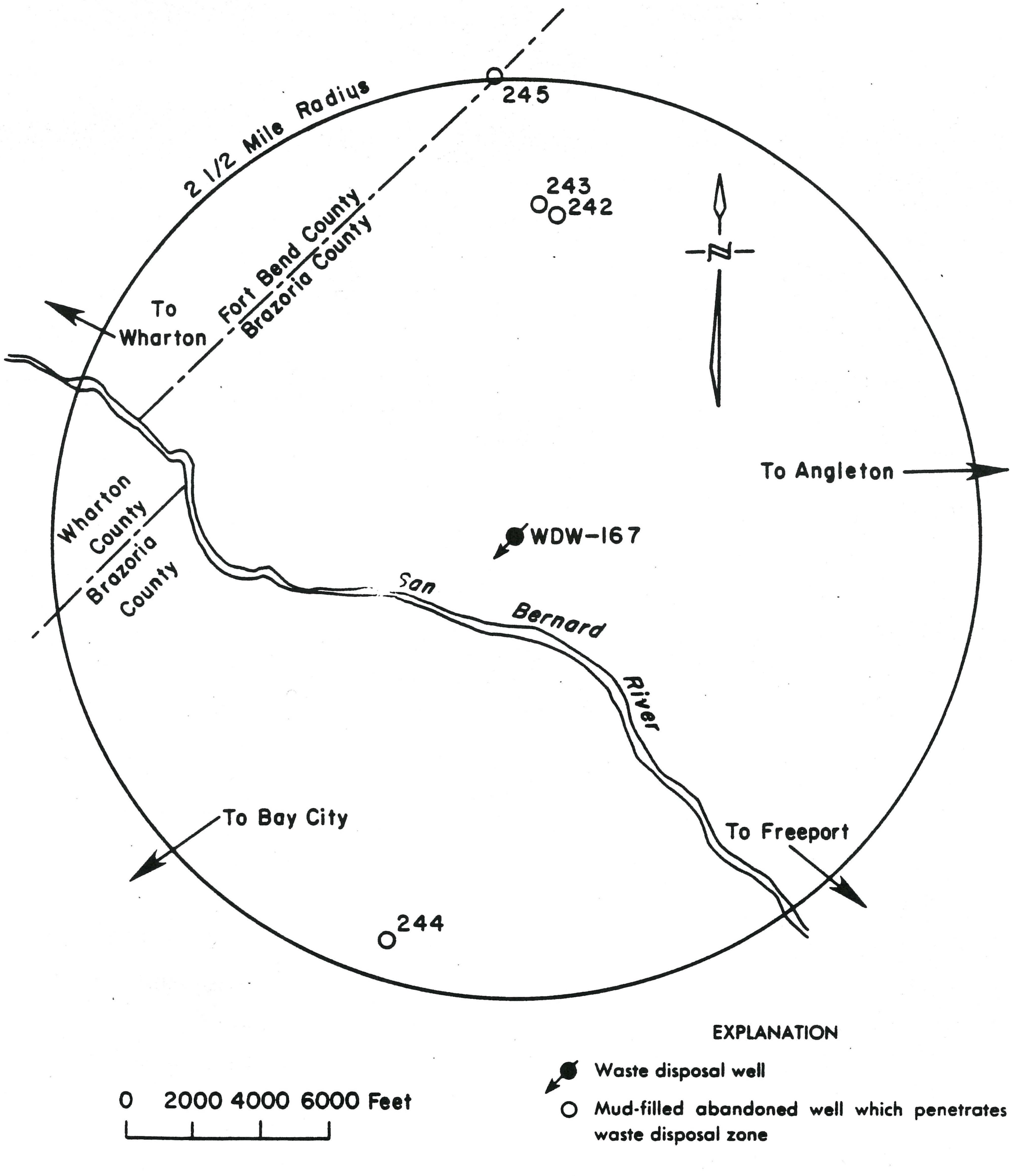


Figure 26--Area of review for Wastewater, Inc. waste disposal well, Guy Facility, Brazoria, Fort Bend, and Wharton Counties

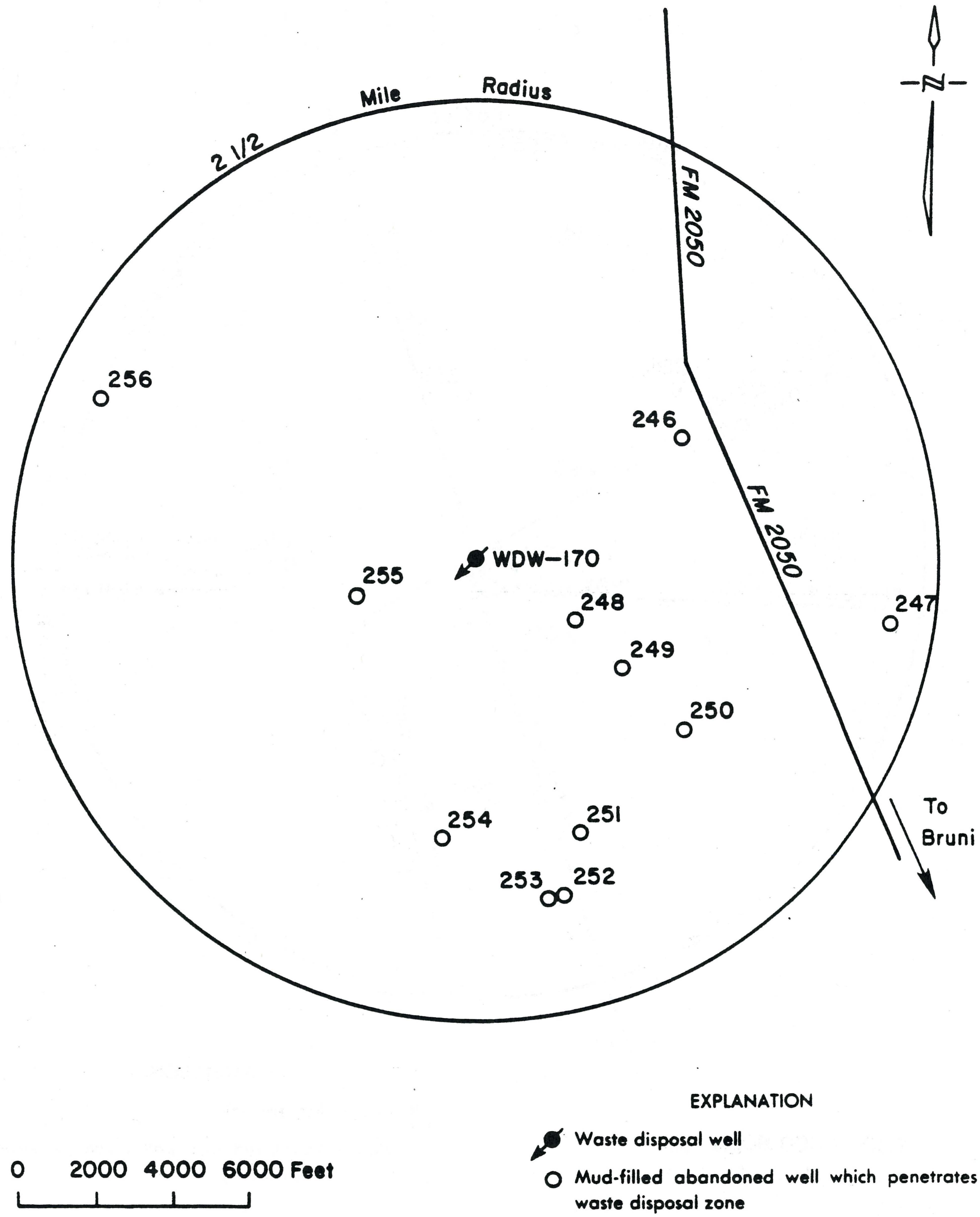


Figure 27--Area of review for Westinghouse Electric Corp. waste disposal well, Bruni Mine, Webb County

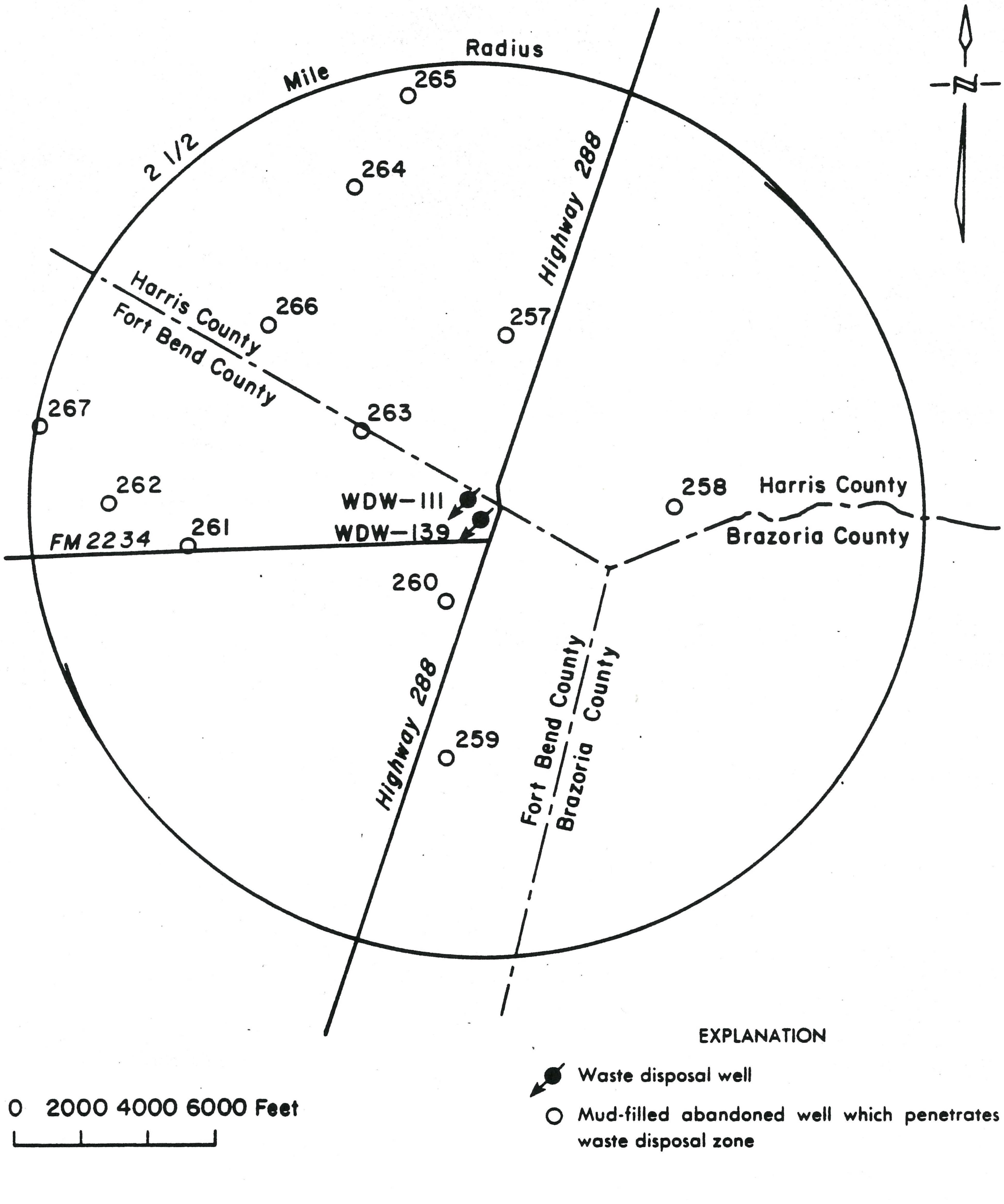


Figure 28--Area of review for Witco Chemical Co. waste disposal wells, Almeda Road Plant, Brazoria, Fort Bend, and Harris Counties

APPENDIX

Summaries of Literature and Personal Communications

Annis, Max R., August, 1967, High-Temperature Flow Properties of Water-Base Drilling Fluids: Journal of Petroleum Technology 1074-1080.

SUMMARY:

A study of mud rheology and gel properties was conducted in the laboratory to investigate the effects of time, temperature and mud composition. Included in the results was some data on gel strengths which should be applicable to a mud column in an abandoned well.

Investigation of a quiescent bentonite mud revealed that gel strength increased with time and temperature. On a given system the mud becomes more non-Newtonian with temperature. Gel strengths based on the breakdown of a gel increases indefinitely with time. As the bentonite concentrations are increased, gel strength and viscosity also increased. Gel strengths, and viscosity, are influenced in an unpredictable manner by the type of mud and electrolyte additives. Addition of sodium hydroxide, for instance, is a common deflocculant which lowers both gel strength and viscosity. Gel strengths of muds are controlled in part by electrical forces between particles and in part by mechanical interaction between particles (the more particles, the more interference between particles).

Under reservoir conditions much greater time is involved, and fluids from the mud are lost to the formation. Both of these factors would tend to increase the gel strength of the mud remaining in an abandoned well. Use of the more conservative gel strengths observed in the laboratory should insure that gel strengths assumed for reservoir conditions are overly conservative. It appears that a gel strength of 20 to 25 pounds per 100 square feet could be safely assumed.

CONCLUSIONS:

1. Mud gel strengths increase indefinitely with time
2. Mud gel strengths increase with temperature
3. Gel strengths are influenced in an unpredictable manner by the mud and electrolyte additives.
4. Addition of sodium hydroxide is a common deflocculant which lower both gel strength and viscosity
5. Mud gel strengths observed in the laboratory would probably increase under reservoir conditions due to the greater time involved and fluid loss to the formation.

Barker, Steven E., 1981, Determining the Area of Review for Hazardous Waste Disposal Wells: M.S. Thesis, University of Texas at Austin.

SUMMARY:

The ultimate gel strength of mud under bore hole conditions bears no direct relationship to the standard gel strength tests conducted on drilling fluids. Following abandonment of a well the mud in the bore hole is subjected to conditions that differ significantly from surface conditions. At formation depths encountered for disposal of hazardous wastes temperatures range from 80 to 300°F, pressures range from 400 to 5,000 psig and residence times generally exceed 5 years.

Water based muds commonly used, develop high gel strengths after prolonged periods of quiescence. The gel strengths attained vary widely depending on chemical and physical properties. Information presented in this paper indicates that gel strengths do not follow any well established prediction of long term gel strengths with time. In all cases observed gel strengths increased with time. Garrison (Barker p. 95) in a study of California bentonites revealed that gel strengths follow a generalized mathematical relationship with constants that vary with the chemic and physical characteristics of the drilling fluids.

The pressure necessary to break the gel strength of a static mud column varies directly with the gel strength and column heights and inversely with the hole diameter.

Oil base muds lack gel strength and wells drilled with this fluid should be evaluated by an alternate procedure.

CONCLUSIONS:

The following conclusions were drawn from the portion of the pape dealing with the gel strength investigation:

1. Gel strengths of muds which remain undisturbed in wells do increase with time.

2. Information presented in this paper indicates gel strengths in wells do not follow any well defined prediction over a long term.

3. A study of California bentonites revealed that gel strengths can be described by a generalized mathematic equation with constants that vary with chemical and physical properties.

4. A gel strength of 20 lb/100 ft^2 represents the minimum value that would be expected to be encountered when evaluating abandoned wells drilled with water base drilling fluids.

5. The pressure required to break the gel strength of a static mud column varies directly with the gel strength and column height and inversely with the hole diameter.

Cox, William, February 26, 1986, Personal Communication: Three Sta
Oil Co., Houston, Texas.

SUMMARY:

William Cox described his years of experience in drilling well for Exxon as an independent oil operator. Much of Cox's work included drilling on the flanks of gulf coast salt domes and in th shallow sands overlying the salt domes. Cox explained the common problem of bit deflection toward the salt stock when drilling intc the steeply upwarped strata on the flank of a salt dome. Use of extra drill collars and very slow penetration rates are required t obtain a straight hole in this situation. Cox indicated that many of the wells in his experience were dilled with "native mud" consisting of just water and drill cuttings. This native mud invariably exceeded 9 pounds per gallon, and frequently had to be thinned by addition of more water to the hole.

CONCLUSION:

Native drilling muds in abandoned wellbores drilled by rotary rigs, exceed 9 pounds per gallon.

Davis, Ken E., November 12, 1985, Address to U.S. Environmental Protection Agency Region IV, Mud-in-Annulus Workshop, Atlanta.

SUMMARY:

The maximum reservoir pressure that mud in a well will withstand before interformational fluid flow will occur, is equal to the combined resistive effects of the mud column hydrostatic weight, and the gel strength of the mud. The minimum gel strength of drilling mud in a well is a direct function of both the initial gel strength of the mud as determined by laboratory tests, and the length of the mud-filled interval, and an inverse function of the diameter of the well.

Most of the information needed to evaluate the ability of mud in a well to prevent interformational fluid flow, may be obtained from operator's well records, drilling and plugging reports, well log headings, and mud company records. In the absence of mud data specific for a well in question, a mud density of 9.5 pounds/gallon, and an initial mud gel strength of 25 pounds/100 feet^2 may be used for conservatively evaluations.

Once reservoir pressures attain a level sufficient to initiate interformational fluid flow through a mud-filled interval of a well, the channels created in the mud may not readily heal when the mud is returned to static conditions.

Besides considerations of mud column hydrostatic weight and mud gel strengths, other factors which may prevent interformational fluid flow in wells are, (a) the hydration swelling of water sensitive clay strata, (b) sloughing or caving of unconsolidated sand strata, and (c) low permeability plugs formed from the settling of native muds or barite-weighted muds, and from the hardening of lime or gypsum-based muds.

CONCLUSIONS:

1. A mud-filled interval of a well will prevent interformational fluid flow, provided that reservoir pressures do not exceed the combined resistive effects of the mud column hydrostatic weight, and the gel strength of the mud.

2. A mud density of 9.5 pounds/gallon and an initial mud gel strength of 25 pounds/100 feet^2 may be used for conservative evaluations of abandoned wells for which specific mud data is not available.

3. Mud gel strength generally increases with time and temperature.

4. Once gel strength of a mud has been exceeded by excessive reservoir pressures, the channels created in the mud may not readily heal when the mud is returned to static conditions.

5. Natural wellbore instability, and settling or hardening of some types of drilling muds may prevent interformational fluid flow within wells.

Deutsch, M., 1963, Ground-Water Contamination and Legal Controls in Michigan: U.S. Geological Survey Water Supply Paper 1691.

SUMMARY:

Concerning abandoned wells, Deutsch reported that vertical leakage of highly mineralized water through unplugged wells or test borings has caused extensive contamination of fresh water supplies over the last 100 years in Michigan. In instances where wells were not cased, as is common in hard bedrock formations, interformational flow of waters has occurred in response to the artesian pressures under which they were confined. In 1939, in Kent County, Michigan, it was concluded that a number of oil wells and test holes drilled between 1935 and 1937 at a location about 1/2 mile upgradient from water supply wells, had communicated high-chloride water from deep formations into the local fresh-water aquifer.

Contamination of drinking water by way of unplugged wells has also occurred in areas of the Saginaw Lowland in Michigan. Here, numerous cased wells were corroded by native formation brines, and the brines entered the aquifer used for drinking water supplies.

CONCLUSIONS:

1. Vertical leakage of highly mineralized waters through unplugged wells or test borings, in response to artesian pressures under which they have been confined, has caused extensive contamination of fresh-water supplies over the last 100 years in Michigan.

2. Brine contamination of fresh-water aquifers by way of unplugged wells and test borings has been documented for uncased holes and for wells with corroded casing.

Gray, George R., and Darley, H.C.H., 1981, Composition and Properties of Oil Well Drilling Fluids: Gulf Publishing Company, Houston, Texas

SUMMARY

The book on drilling fluids by Gray and Darley deals primarily with oil and gas well drilling. Some parts of the book might also be applicable to mud plugging of abandoned wells.

In their chapter on rheology of drilling fluids, data on quiescent muds are presented that indicate mud gel srengths increase with time. Empirical data has been fitted to an equation which increases linearly with time. Extrapolation of this data suggests that gel strength would increase indefinitely with time. However, the increase in gel strength noted after an extended time span would be insignificant.

Limited data presented by Gray and Darley also indicate that gel strength increases as the temperature is increased. Trends for the initial gel and 30 minute gel strengths demonstrate this property (Gray and Darley, p. 232). The explanation for this phenomenon is that high temperatures increase the interparticle attractive forces, so that the gel strength is increased accordingly.

The effects of temperature and time in increasing gel strength of muds are significant during drilling operations, when mud circulation is interrupted in the lower portions of the hole while making at trip out of the hole. The gel strength of this undisturbed (uncirculated) mud must be exceeded by the mud pump pressure in order to reestablish mud circulation and resume drilling. When lime-based muds have been used, semi-solid cement-like masses have been noted which are difficult to move. Extrapolating laboratory properties to wellbore conditions in abandoned wells would postulate that gelled or solidified muds aid in confining fluids in over-pressured reservoirs.

Humble Oil and Refining Company (now Exxon) experienced unexpected blowouts while drilling in the Conroe Field. The blowouts occurred while withdrawing drill pipe from the hole, although the mudweight was more than adequate to suppress the reservoir pressure. Investigation revealed the gel strength of the mud had increased in the well to the point that the gelled mud clung to the pipe and swabbed the well, allowing gas and oil to invade the wellbore.

Though conditions in abandoned wells were not specifically covered in Gray's and Darley's book, it is evident that muds in an abandoned well are subject to long time spans, high temperatures, and filtrate losses. Since all these factors tend to increase gel strength, the lab gel strengths reported should be conservative estimates of mud gel strength in an abandoned well. Therefore, use of a conservative gel strength of 20 to 25 pounds per 100 square feet, would ensure that the pressure-retaining capability of a mud gel is not overestimated.

CONCLUSIONS

1. Mud gel strength increase indefinitely with time.

2. Mud gel strength increase with temperature.

3. Mud gel strengths observed in the laboratory should be lower than those present in the reservoir. Therefore, assuming a gel strength of 20 to 25 pounds per 100 square feet, as observed in the laboratory, should be conservative for use in the field.

Hellinghausen, Jack, November 14, 1985, Personal Communication: Atlantic-Richfield Co., Dallas, Texas.

SUMMARY:

This discussion with Hellinghausen was primarily concerned with older wells drilled and abandoned in the 1920's and 1930's. Information concerning gel strength on native muds used in that era is practically nonexistent but he thought the gel strength was low.

Wells drilled during the 1920's generally ranged from 500 to 1000 feet. A 2500 foot depth was considered to be relatively deep. During the 1930's a well could readily be drilled from 3000 to 4000 feet with an occasional well as deep as 6000 feet. Plugging an abandoned well was usually accomplished by dumping about 25 sacks of cement down the annulus or pumping some cement down to the packer. Cement "plugs" placed in the well mixed with the mud and most probably were ineffective plugs. Wells drilled with the cable tool are dry open holes that could be sealed by dropping cement in the hole with a bailer.

Some of the old wells that were drilled and abandoned have mud plugs that have set up and become more dense than the surrounding formations. Drill bits have been sidetracked when drilling out the old holes. Also holes that were drilled at that time were crooked, as only short drill collars were available which allowed the hole to drift. It was also mentioned that during abandonment of some of these old wells all the junk from the drill site was dumped in the well bores which would make drilling out of these holes more difficult.

CONCLUSIONS

1. Gel strengths of native muds left in wells of the 1920's and 1930's were unknown

2. Wells drilled in the 1920's averaged about 1000 feet in depth with a maximum of about 2500 feet. Wells drilled in the 1930's generally ranged from 3000 to 4000 feet in depth with a maximum depth of about 6000 feet.

3. Plugging of wells during that time generally consisted of a 25 sack cement plug dropped in the annulus or pumped to the packer. As a result these plugs were probably mixed with the mud rendering them ineffective.

4. Mud plugs that have setup and become more dense than the surrounding formation have been encountered when drilling out old well bores.

5. During abandonment of many old wells junk from the surrounding drill site was dumped in the well bores.

Jeffery, David, and Istvan, John, January 9, 1986, Personal Communication: PB-KBB Inc., Houston, Texas.

SUMMARY:

David Jeffery and John Istvan were interviewed during a visit to the agency on other business. During a discussion of mud properties both individuals agreed the most important property of a mud to control pressure in an abandoned well is the weight, or density, of the mud. Gel strength makes a small contribution towards controlling pressure in the borehole and should be regarded only as safety factor in their opinion. Muds containing bentonite are relatively stable gels when quiescent and do not setup or solidify. As a consequence they would be expected to be displaced from an unplugged open well if the hydraulic head and the gel strength were exceeded by the reservoir pressure. Lime base muds used prior to bentonite additives tend to solidify blocking the well bore against fluid flow.

In a discussion concerning abandoned wells located on theGulf Coast it is believed that abandoned open hole wellbores heal over due to the relatively unconsolidated formations. However, if casing is left in the hole a channel is provided for fluids to migrate between permeable zones or to the surface In West Texas hard rock country the boreholes of abandoned wells tend to remain unchanged for sometime. In some areas the Red Bed clays tend to close off wellbores within a few days and some cases in a few hours.

Wells drilled before the mid-thirties most probably do not exceed 3000 to 3500 feet depth due to the limitations of the drilling equipment. These wells were generally too shallow to penetrate permeable zones that might be considered for a waste injection zone. While discussing this issue it was suggested that a depth of at least 2500 feet (3500 feet would be preferable) should be required for a waste disposal zone. Any reservoir considered should be evaluated on its own merits.

Reentry of abandoned wells in the Gulf Coast area has disclosed that open wellbores have healed over sufficiently to prevent migration of fluids between formations. In one case the old wellbore could not be followed. In another case mud appeared on the shaker screen indicating the hole was being followed, however, the hole had healed over so that fluid migration would be prevented.

CONCLUSIONS:

1. Mud weight, or density, is the most important property of mud to control migration of fluid in wellbore.

2. Gel strength makes a small contribution to control fluid migration and should be regarded as a small safety factor.

3. Abandoned wells in unconsolidated formations of the Gulf Coast will probably heal over thereby preventing fluid migration.

4. Abandoned well bores in West Texas are more likely to remain intact where Red Bed clays are known to exist, these wellbores may be closed.

5. Any casing left in an abandoned well can provide a channel for migration of fluids to ground water zone or to the surface.

Johnson, R.L., November 19, 1985, Personal Communication: Amoco Production Company (USA), Houston, Texas.

SUMMARY:

Johnson described his experience in reentering wells for a waterflood project near Wichita Falls. In general, the mud in the reentered holes was found to have thickened to a gel strength greater than that of the original mud conditions. However, no evidence was found that such thickened muds ever solidified completely.

Johnson also supervised the 1983 reentering and plugging of an abandoned well located near the Amoco industrial waste disposal well site in Texas City. This well had originally been drilled and abandoned in 1944. Amoco was able to follow the original borehole, using a bit to wash the old mud from the hole to total depth. The old mud appeared to have thickened over 40 years, and there was no evidence of fluid flow through the borehole during this period of time.

Bridging of the unconsolidated or water-sensitive sediments in the borehole wall may completely seal a well. Johnson cited the commonplace difficulty of getting tools and casing strings downhole in the Gulf Coast region due to natural borehole sealing.

Johnson further indicated that even when reservoir pressures are sufficient to displace the hydrostatic weight of borehole mud, the buildup of impermeable mud filter cake on the borehole wall may retard or prevent interformational flow of fluids.

Johnson stressed that no plugging and abandonment technique is absolutely failsafe. Even cement plugs may be ineffective in plugging a well if they are not set properly and confirmed by tagging.

CONCLUSIONS:

1. Experiences in reentering abandoned wells have found the borehole mud to have thickened over time, but not to have solidified.

2. Difficulty in running tools and casing strings into newly drilled wells indicates a tendency for natural borehole sealing in Gulf Coast-type unconsolidated sediments.

3. The build-up of impermeable mud filter cake on borehole walls may retard or prevent interformational flow of fluids.

4. No plugging and abandonment technique is absolutely failsafe. Care should be taken to confirm that mud and cement have been properly placed in an abandoned well.

Johnston, O.C. and Greene, C.J., 1979, Investigation of Artificial Penetrations in the Vicinity of Subsurface Disposal Wells - Technical Report: Texas Department of Water Resources.

SUMMARY:

In considering permit applications for waste disposal wells, artificial penetrations should be evaluated by reviewing completion and plugging records in the subject area, to identify improperly plugged wells. The pressure increase caused by the proposed injection program should be calculated for each potential problem well, using estimated values for transmissibity and storage in the nonequilibrium formula developed by Theis (1935). Generally, a well that has been properly completed or abandoned is one where interformational fluid transfer does not occur, or will not occur as a result of changes in reservoir pressure.

Due to the plastic nature of most Tertiary shales, abandoned well bores probably do not remain open for long periods of time. However, for technical evaluations in conjunction with waste disposal well permitting, uncased boreholes are assumed to remain open and full of drilling mud. In the west and north-central part of Texas, a wellbore or an uncemented annulus may remain open for indefinite periods of time, and often drilling fluids and cement may not be in the wellbore or annulus because of lost circulation zones.

Where calculated reservoir pressures resulting from injection are sufficient to overcome the resistive effect of the hydrostatic pressure of mud in an improperly completed or abandoned well, the well should be reentered and properly plugged, or a reservoir pressure monitor well should be completed. Operation of a pressure monitor well will enable the pressures within a reservoir to be limited to prevent the possibility of fluid flow through improperly plugged wells.

CONCLUSIONS:

1. Completion and plugging records of artificial penetrations near proposed waste disposal wells should be reviewed to determine which abandoned wells require remedial plugging or reservoir pressure monitoring to prevent interformational transfer of fluids.

2. Abandoned wellbores filled with mud, and wellbore closure by natural formation wall instability are reasonable conditions for the Gulf Coast area.